

Teaching Electric Field And Electric Potential Using A Low-Cost Water-Based Mapping Apparatus

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Abstract: Understanding electric field and electric potential remains challenging for many students because these quantities are spatially distributed, abstract, and not directly observable. This study presents a low-cost experimental apparatus that enables students to map electric potential and infer electric field behavior using an electrolytic water medium. Two parallel electrodes are immersed in tap water, and a constant low potential difference is applied. Using a high-impedance voltmeter probe, students measure spatial variations of the potential along predefined paths and compare the results with theoretical predictions for a uniform electric field. Three instructional investigations are reported: (i) verification of linear potential variation in a uniform field, (ii) experimental demonstration of the directional (vector) nature of the electric field, and (iii) examination of the path independence of electric potential difference. The results show that the measured potential varies linearly with distance between parallel electrodes within experimental uncertainty, and that potential changes along inclined paths scale with the cosine of the angle relative to the field direction. The summation of incremental potential differences along different paths yields consistent overall potential differences within expected measurement uncertainty. The apparatus is inexpensive, easy to construct, and suitable for secondary or undergraduate laboratories. It enables students to connect mathematical expressions for electric field and potential with direct spatial measurements and supports conceptual understanding through hands-on exploration.

Keyword: Physics education research, teaching electric field, teaching electric potential, innovative teaching material, physics laboratory design.

1.INTRODUCTION

Physics aims to explain fundamental principles governing natural phenomena, and among these principles, electricity occupies a central position due to its foundational role in understanding interactions between charges and the structure of matter [1, 2]. Within this domain, the electric field serves as one of the core conceptual tools, offering a framework for explaining how charges influence their surroundings and exert forces on other charges [3]. Despite its theoretical importance, the electric field is consistently reported as one of the most abstract and challenging concepts for students to comprehend [4]. Its invisibility, reliance on symbolic formalism, and heavy mathematical representation make it difficult for learners to form coherent mental models of its behavior. As

a result, misconceptions and fragmented understandings of electric field and electric potential frequently persist even after traditional instruction [5].

A considerable body of physics education research has documented these difficulties. Maloney et al have shown that students frequently rely on algorithmic problem-solving without developing a coherent conceptual model of field behaviour [6]. Likewise, McDermott and Shaffer found that introductory-level students often misconceive potential difference, superposition, and the role of circuit elements. These studies consistently indicate that students tend to rely on intuitive ideas or everyday analogies that are inconsistent with scientific explanations [7]. Similarly, A root cause of these learning challenges lies in the high degree of abstraction inherent to electric fields and electric potential. Unlike mechanical phenomena that can be directly observed or physically experienced, electric fields are typically introduced through symbolic representations such as vector diagrams, mathematical equations, and graphs. Although these tools are essential for advanced study, they require students to translate symbolic information into a physically meaningful mental model an intellectual leap that many find difficult. Campos et al. emphasize that this gap between symbolic representation and physical interpretation often leads learners to develop fragmented knowledge structures rather than integrated conceptual understanding. This explains why many students are able to solve algorithmic problems involving electric fields but still struggle to articulate underlying principles or visualize field distributions in space [8].

Because of these challenges, physics education researchers have increasingly emphasized the importance of instructional materials, active learning environments, and hands-on experimentation. Well-designed simulations and interactive computer environments have been shown to enhance conceptual understanding by enabling students to manipulate field configurations, observe spatial changes, and receive immediate feedback [9]. In addition, material-supported instruction—particularly through low-cost, adaptable tools—has been found to promote long-term retention, deeper conceptual understanding, and improved problem-solving skills [9]. In the context of electricity, where spatial visualization is essential, the value of concrete instructional materials becomes especially pronounced.

The present study was designed to address persistent conceptual difficulties associated with electric field and electric potential by developing a water-based experimental apparatus that allows students to measure, map, and interpret potential distributions between parallel plates. The experimental study comprises three complementary components. First, the uniformity of the electric field between parallel plates is evaluated by measuring potential changes along certain linear paths. This enables learners to observe the expected linear relationship between electric potential and distance in a uniform field. Second, the vector nature of the electric field is explored by comparing potential differences along paths that form a known angle with the field direction, allowing the relationship between field components and direction to be examined experimentally. Third, the conservative property of electric potential—its independence from the measurement path is tested through a comparison of direct potential differences with the summation of potential drops measured along small segments of different paths. Together, these experiments help students connect theoretical expectations with empirical observations and develop a deeper understanding of the physical behavior of electric fields.

Overall, this study contributes to the physics education literature by offering a low-cost, accessible, and pedagogically powerful tool for teaching electric field and electric potential. By integrating theoretical principles with hands-on exploration, the apparatus aligns with contemporary trends emphasizing inquiry-based learning and experiential understanding. Previous research has demonstrated that students develop more accurate and stable conceptual frameworks when they can link symbolic expressions to observable phenomena [10, 7]. In this context, the water-based apparatus presented in this study provides an effective means of helping learners overcome common misconceptions, visualize abstract concepts, and engage in authentic scientific reasoning. The approach holds promise for both secondary and undergraduate instruction, enabling students not only to perform calculations but also to understand and interpret the physical meaning of electric fields and potentials.

2.THEORETICAL BACKGROUND

An electric field may be generated either by static charge distributions or by applied potential differences. In both cases, the electric potential varies with spatial position. In this work, due to simplicity and convenience, electrical potentials created within tap water are measured to demonstrate and teach fundamental relations between the electrical field and electrical voltages.

2.1.Electric field and electric potential difference

General relationship between the electrical field and the electrical potential in differential form is expressed by,

$$\vec{E} = -\vec{\nabla}V \quad (1)$$

In one dimension it reduces to,

$$E(x) = -\frac{dV(x)}{dx} \quad (2)$$

If one integrates the equation (2) from the point A to the point B within the electric field, the potential difference, $\Delta V = V_B - V_A$, can be given by following expression,

$$\Delta V = -\int_A^B E dx \quad (3)$$

If the electric field is uniform and the displacement is parallel to the field then it is straightforward to obtain the following simple formulation,

$$\Delta V = -E |AB| \quad (4)$$

where $|AB|$ represents the distance between the point A and B within the electric field.

2.2.Potential variation along an angled path

In equation (2), the electrical field and the displacement are obviously vector quantities; hence the vector relation of these two quantities can be written as the scalar product of the two vectors, $dV = -\vec{E} d\vec{x}$, which leads to,

$$dV = -E dx \cos \theta \quad (5)$$

where θ denotes the angle between the electric field and displacement vectors. This relation can also be expressed in terms of the change of the quantities, $\Delta V = \vec{E} \Delta \vec{x}$, which leads to,

$$\Delta V = -E \Delta x \cos \theta \quad (6)$$

which can be employed for any straight path having an angle with the field.

2.3.Path independence of potential difference

It is also possible to express the equation (3) along any closed path which can be given by,

$$\Delta V = -\oint E dx = 0 \quad (7)$$

which expresses that the electrostatic fields are conservative. This can be verified by measuring the potential differences along different paths between specified two points and in this case, it is possible to write that,

$$\sum_{i=1}^N (\Delta V_i)_{A-B \text{ Path}} = \sum_{i=1}^N (\Delta V_i)_{A-C \text{ Path}} \quad (8)$$

where $(\Delta V_i)_{A-B \text{ Path}}$ and $(\Delta V_i)_{A-C \text{ Path}}$ denotes the tiny potential difference along the selected path. This equation can easily be employed to verify the path independence of the electrical potential difference within the electric field.

3.METHOD

3.1.Water as conducting medium

This work simply considers and suggests that ordinary water can be employed as a conducting medium to demonstrate and teach the fundamental relations between the electric potential and field. Water consists of electrically neutral molecules and, in its pure form, is a poor electrical conductor because it contains very few free charge carriers. Nevertheless, ordinary tap water always contains significant dissolved salts that dominates the electrical conduction. On the other hand, if one applies a small amount of voltage the number of ions increases in accordance with the chemical reaction of, $H_2O \rightarrow H^+ + OH^-$ which also transforms water containing free ions of (H^+) and (OH^-) that also causes electrical conduction. In a weakly conducting liquid with conductivity σ , steady currents obey $\vec{J} = \sigma \vec{E}$ and under steady conditions and approximately uniform conductivity within ohmic regime, the potential distribution satisfies, $\nabla^2 V = 0$, which is the same equation that describes electrostatic potential in charge-free regions. Thus, mapping potential in the water medium provides an analogue of electrostatic field mapping. Ordinary tap water with auto-ionized molecules has a room temperature specific conductivity between $50 \mu S/cm$ and $500 \mu S/cm$ and accordingly it is appropriate employ tap water to teach fundamental electrical properties of matter. When low voltages (e.g. 9 V) are used, current flow remains small and heating, polarization and electrolysis effects are minimal, allowing stable measurements for instructional purposes.

It is crucial at this point to express that the parallel conducting plates are not ideally electrostatic due to fringing fields, finite plate size, electrode polarization and possible leakage current flows. Therefore, in this approach quasi electrostatic field is maintained not a vacuum electrostatic field. Hence, it is legitimate to write $\nabla J = \nabla(\sigma E) = \nabla(\sigma \nabla V) = 0$.

3.2.Experimental apparatus

The experimental setup, shown in Figure 1, consists of several components, namely a glass water container with a size of 27cmx40cm, ordinary tap water, a few mm scaled A4 papers (graph papers), a voltage source (9V battery), two conducting (Al) plates or rods for electrodes, a voltmeter, crocodile and connection cables, mechanical stands and arms.

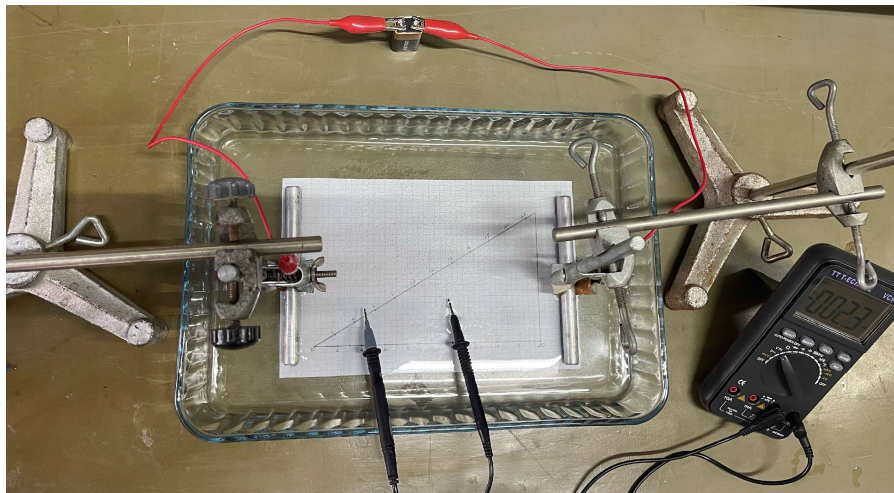


Figure 1: The photography of the experimental setup showing all parts used to carry out the measurements.

To create a uniform electric field, two identical parallel aluminum plates, positioned approximately 20 cm apart, were utilized. A constant potential difference of 9V was applied across these plates using an ordinary 9V battery. A digital multimeter with high input impedance and a thin, conductive-tipped potential probes were used to measure the electric potential within the water medium. The probes were mounted on a precise three-dimensional positioning mechanism allowing for high-accuracy

recording of potential values at various points within the water-filled tank. The low-potential (typically grounded) plate served as the reference point for all potential measurements.

Through this setup, students are able to investigate how electric potential varies with position, how electric field direction influences potential change, and whether electric potential differences remain consistent across different paths. Water-based field mapping systems offer a particularly effective approach for overcoming the abstract nature of electric field concepts. Because ordinary water contains ions, electric potential differences can be measured with good sensitivity across many spatial points. This allows equipotential lines and electric field patterns to be visualized directly, providing students with a tangible representation of otherwise invisible physical quantities. The method is inexpensive, easy to reproduce, and adaptable for both high school and undergraduate laboratory settings. More importantly, it enables learners to connect theoretical knowledge with direct observation, thereby facilitating conceptual change and strengthening scientific reasoning.

4. MEASUREMENT PROCEDURE

4.1. Relation between electric potential and electric field

In order to verify the scalar relation between the electric field and electric potential within a uniform or non-uniform electric field, it is legitimate to perform potential measurements relative to a fixed point along a straight path. Figure 2 shows the uniform electric field created by constant voltage applied between the two Al plates within the water tank and the paths A-B, A-C and B-C in addition to equipotential lines.

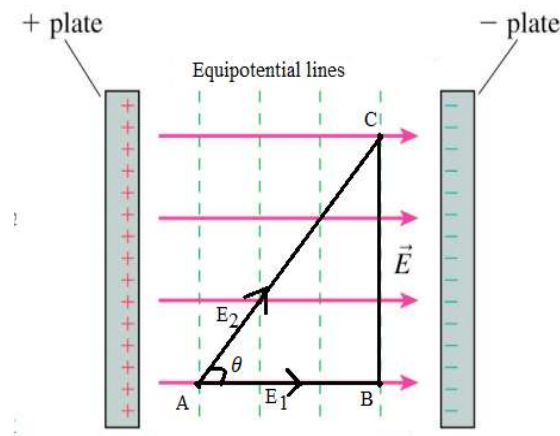


Figure 2: Parallel plate electrodes within the water container and the paths of A-B, A-C and B-C together with the equipotential lines.

The actual scalar relation between the electric potential and electric field can be obtained by employing the general definition given in the equation (2). In order to accomplish the task, it is possible to measure the electric potentials relative to a fixed point on the path and as a function of distance and plot the graph of electric potential V as a function of distance x and determine the mathematical relation $V(x) = f(x)$. Once the relation is determined, by taking the first derivative directly leads to the electric field along that straight path, $E(x) = -\frac{dV(x)}{dx}$. In the case of uniform electric field, the relation appears to be in the form of $V(x) = mx + b$ and in this case obviously, the electric field is given by $E = |m|$. If the electric field is not uniform, then the graph would not be linear and the derivative would be position dependent. In this case, the electric field along A-B is called E_1 and along A-C is E_2 and the angle between them is θ then the equation of $\frac{E_2}{E_1} = \cos \theta$ is obviously validate. Hence, the electric field magnitudes obtained from the measurements ought to be verifying this basic relation. Figure 3 shows the actual photography of the

scaled paper sheet employed to measure the potentials along two different paths. Figure 4, on the other hand, shows the actual measurement apparatus.

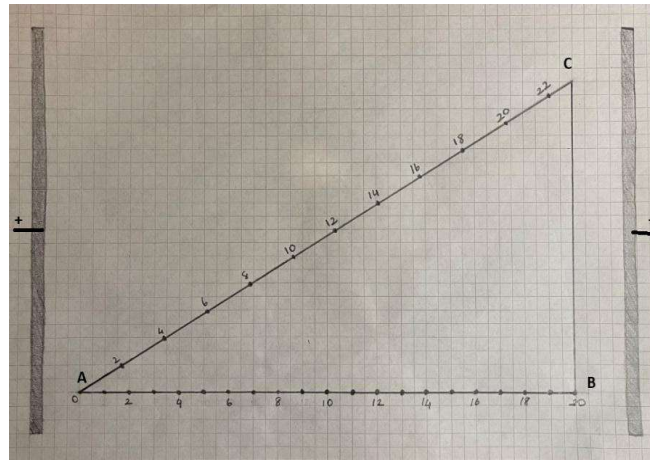


Figure 3. Actual scaled paper with predetermined potential measurement paths in uniform electric field within the water medium.

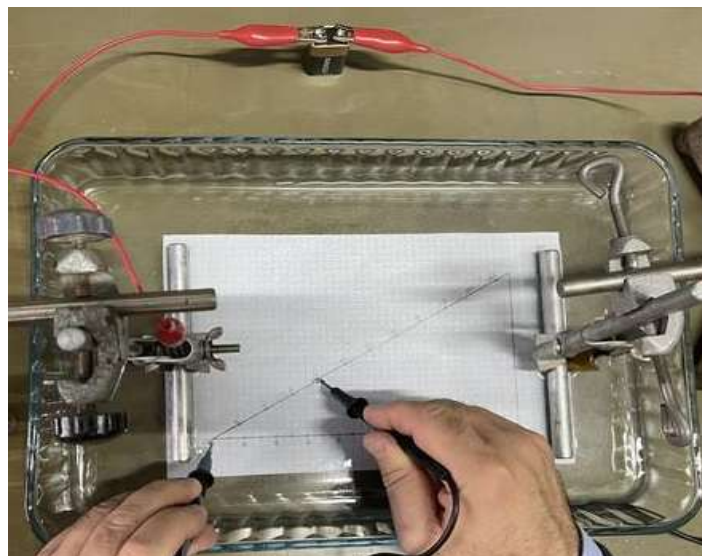


Figure 4. The apparatus showing the measurement of electric potential as a function of distance within water by using multimeter probs.

4.2. Vector character of electric field

In order to demonstrate and teach the vector character of the electric field it is legitimate to measure the potential differences across same distances along two different paths.

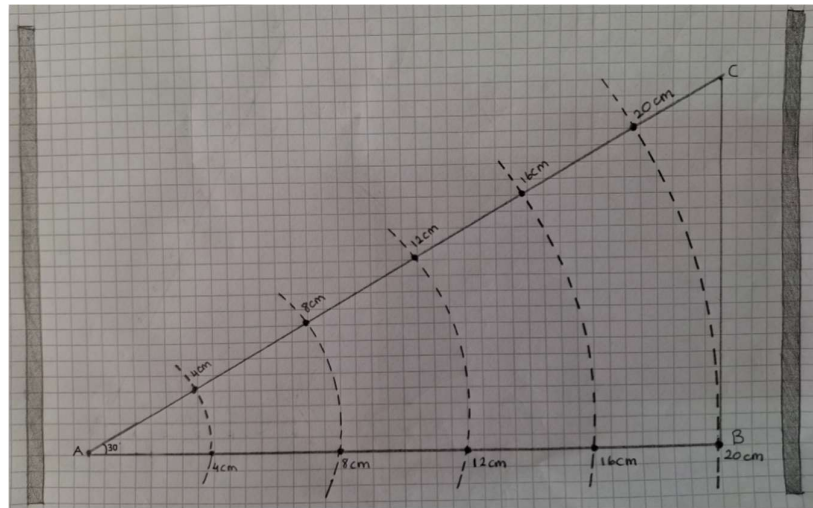


Figure 5. The figure showing the same and considered $|MN|$ distances along A-B and A-C paths.

The general relation between the potential difference and electric field is given by $\Delta V = \vec{E} \Delta \vec{x} = E \Delta x \cos \theta$. For the same angle, for instance say $\theta = 30^\circ$ in this case and for the distances along A-B and A-C say $\Delta x = |MN|$ one can measure the potential differences. In this case measuring the potential difference along A-B (E_1) across $\Delta x = |MN|$, must be equal to $(\Delta V)_1 = E_1 |MN| \cos 0 = E_1 |MN|$. In the same way measuring the potential difference along A-C (E_2) across $\Delta x = |MN|$ gives $(\Delta V)_2 = E_2 |MN| \cos 0 = E_2 |MN|$. In this case the ratio of measured potential differences must be verifying the equation of, $\frac{(\Delta V)_2}{(\Delta V)_1} = \frac{E_2}{E_1}$. Therefore experimentally determined potential ratios of $\frac{(\Delta V)_2}{(\Delta V)_1}$ ought to be equal to the actual cosine of the angle, that is $\frac{(\Delta V)_2}{(\Delta V)_1} = \cos \theta$. This result clearly demonstrates the vector property of the electric field, expressing that $E_2 = E_1 \cos \theta$, stating that the electric field E_2 is in fact a component of E_1 .

4.3. Path independence of potential differences

The theory expresses that the potential difference between two points is equal to the sum of sequential potential differences along any arbitrary path. Hence, sum of sequential voltage differences along the path of A-B and A-C ought to be equal, $\sum_{i=1}^N (\Delta V_i)_{A-B \text{ Path}} = \sum_{i=1}^N (\Delta V_i)_{A-C \text{ Path}}$. In order to verify this equation one can measure sequential potential differences along A-B and A-C paths and add the voltages together. The overall potential difference directly measured across A and B ought to also be equal to the sum. The same procedure can obviously be applied to the path of A-C.

5. RESULTS

5.1. Determining the magnitude of the electric field

In order to determine the magnitude of the electric field along a certain path, two different measurement paths were predetermined between parallel plates, and potential values at sequential points along two paths were measured. One of these two measurement paths was chosen to be horizontal and the other one diagonal as shown in figure 3. The plots of electrical potential as a function of distance are shown in Figure 6. The upper line belongs to the path of A-B and therefore to the electric field of E_1 and the lower line belongs to the path of A-C and therefore to the electric field of E_2 . The actual relation between the electric potential and distance for the path of A-B is found to be $V(x) = 0,3249 x + 0,0334$. It is appropriate to estimate the actual electric field by employing the theoretical definition of $E(x) = \frac{dV(x)}{dx}$ which leads to the result of $E_1 = 0,3249 \frac{V}{cm}$. The same approach can be used to estimate the electric field E_2 . Similarly, the relation between the electric potential and distance for the path of A-C is found to be $V(x) = 0,2912 x - 0,1058$. It is similarly direct to find the electric field as $E_2 = 0,2912 \frac{V}{cm}$.

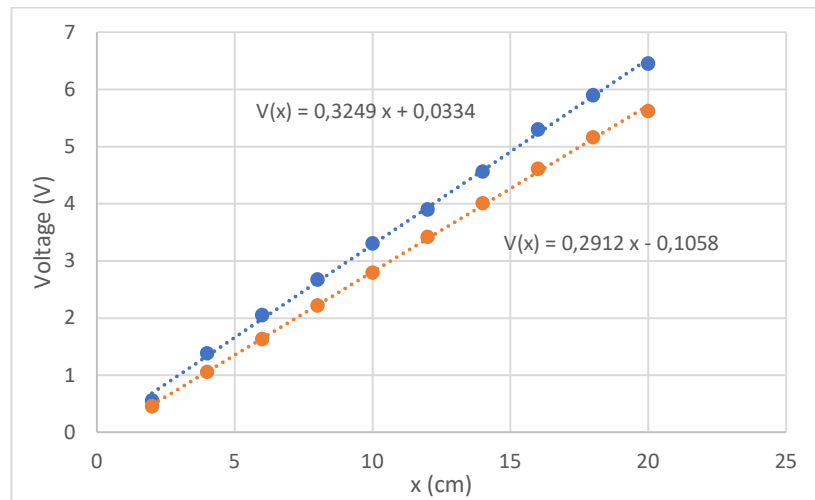


Figure 6. Potential (V) vs. distance (x) graph for horizontal and diagonal measurement paths in an electric field within the water.

5.2. Investigating vector nature of electric field

In this set of measurements, potential differences were measured along two different paths across the same distances, as shown in Figure 5. The angle in this specific measurement directions was set to $\theta = 30^\circ$. In this case, the ratio of voltage along A-B (horizontal path) and the voltage along A-C (diagonal path) is plotted as a function of fixed distances. The actual measurements are given in Figure 7 and the experimental relation based on the graph is found to be $V(x) = 0,9076 x - 0,3648$ which leads to the slope of $\frac{(\Delta V)_{A-B}}{(\Delta V)_{A-C}} = 0,9076$. This experimental result can be compared with the theoretical value of ratio which is $\cos 30 = 0,866$. Based on this result, the relative error can be calculated as $RE = \frac{0,9076 - 0,866}{0,866} = 0,048$, which means that the relative error is 4,8 %.

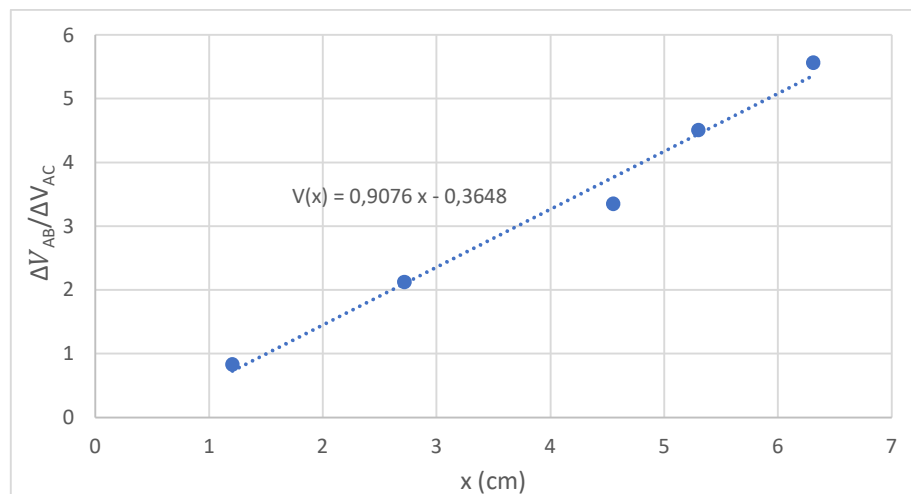


Figure 7. Graph of potential measurements made along linear path and diagonal path.

5.3.Path independence of potential difference and consistency on equipotential lines

In this part of experiments, it is aimed to show that electrical potential has a conservative property, that is, the electrical potential difference between any two points is independent of the path. In this part, it is likewise genuine to show that the points on the equipotential lines have the same potential. In a uniform electrical field, equipotential lines are perpendicular to the electrical field lines. In the experimental setup, points B and C are positioned on the same equipotential line. In this case, the potential difference V_{AB} from point A to point B and the potential difference V_{AC} from the point A to point C are theoretically expected to be equal to each other ($V_A - V_B = V_A - V_C$ so $V_B = V_C$).

In the experiment, the potential difference from point A to point B was measured directly as $V_{AB}=6,66\text{V}$. The potential difference from point A to point C was measured directly as $V_{AC}= 6,45 \text{ V}$. In addition, potential drops were recorded in 2 cm segments for both paths. The measurements and the sums of these measurements are also given in table 1. The *horizontal* path segments represent the voltage drops recorded along the A-B path; the *diagonal* path segments represent the voltage drops recorded along the A-C path. The actual measurements are presented in the Table 1.

Table 1: Path independence of potential difference and equipotential lines experimental data.

Distance x(cm)	Horizontal Path-AB Potential Difference (V)	Diagonal Path-AC Potential Difference (V)
0-2	0,565	0,474
2-4	0,586	0,521
4-6	0,571	0,563
6-8	0,532	0,497
8-10	0,479	0,484
10-12	0,484	0,445
12-14	0,472	0,442
14-16	0,462	0,421
16-18	0,425	0,360
18-20	0,452	0,404
	$\sum V = 5,028 \text{ V}$	$\sum V = 4,991\text{V}$
	Direct Measurement $V_{AB} = 6,66 \text{ V}$	Direct Measurement $V_{AC} = 6,45 \text{ V}$

The relative errors for the horizontal and diagonal paths can be calculated by using the actual measurements. The relative error for the horizontal path is estimated to be $RE = \frac{5,028-6,66}{6,66} = 0,245$ which means 24,5 % relative error. Similarly, relative error for the diagonal path is estimated to be $RE = \frac{4,991-6,45}{6,45} = 0,226$ which means 22,6 % relative error. Large relative errors are attributed to probe positioning errors and cumulative measurement uncertainties.

6. DISCUSSION

The experimental findings obtained in this study were evaluated with respect to the fundamental principles of the electric field formed between parallel plates. The results were examined under three key categories: (1) the linear variation of potential in a uniform electric field, (2) the vector nature of the electric field, and (3) the path-independence of electric potential. Overall, the

findings strongly support theoretical expectations and demonstrate the pedagogical value of the low-cost, water-based experimental apparatus.

The theoretical expectation that the electric potential between parallel plates should vary linearly with distance was unequivocally confirmed by the regression analyses. The close magnitude agreement between the electric field values obtained along the horizontal and diagonal paths indicates that the plates successfully produced a highly uniform electric field. This outcome is pedagogically significant as it enables students to directly observe the fundamental principle that the potential decreases at a constant rate in a uniform field, thereby concretizing this abstract concept [11].

One of the most significant findings is the successful empirical verification of the vector nature of the electric field. Along a diagonal path, the change in potential is influenced solely by the component of the displacement vector parallel to the direction of the electric field. Consequently, the electric field magnitude measured along the diagonal path is expected to correspond to the horizontal field magnitude multiplied by the cosine of the angle between the two paths [8].

The fact that the experimentally obtained ratio closely matches the theoretical cosine value with a low relative error of only 4,8 % demonstrates the high reliability of the measurement procedure and the experimental setup in capturing the directional dependence of the field. This result is particularly valuable for helping students understand vector components, moving beyond purely mathematical expressions to direct physical measurement [6].

Electric potential is defined as a conservative quantity; therefore, the potential difference between two points must be independent of the path taken between them. In this study, the direct potential measurements obtained along the (A–B) and (A–C) paths were very close, exhibiting only a 3,2 % difference, which confirms consistency with this theoretical principle. However, when testing the integral property of potential difference by summing small, sequential segments along each path, significantly larger discrepancies were observed (24,5 % for A–B and 22,6 % for A–C). These considerable deviations may be attributed to two primary factors: 1. Limitations in measurement precision: The inherent difficulty in positioning the probe with millimetric accuracy at each 2 cm interval and the instability in the contact resistance between the probe tip and the water surface. 2. Fringing effects: Near the plate edges, the electric field is not perfectly uniform, causing deviations from the idealized linear summation of potential segments. Despite these sources of error, the experiment provides a crucial opportunity for students to investigate whether a physical quantity is conservative and to engage in authentic scientific reasoning by critically analyzing the sources of error and measurement uncertainties. Thus, the apparatus supports not only conceptual understanding but also the development of essential scientific process skills [12].

7. CONCLUSION

This study has presented an innovative experimental teaching material designed to explore the concepts of electric field and potential using a low-cost parallel-plate system immersed in water. The results demonstrate that even simple measurements conducted with this apparatus enable accurate observation and verification of key physical principles associated with uniform electric fields, vector components, and the path independence of electric potential. The main conclusions of the study are as follows:

1. Uniform electric field is created and measured within the water. The potential–distance graphs along both horizontal and diagonal paths exhibited the expected linear behavior. The close agreement between the electric field magnitudes obtained along these paths confirms that the apparatus effectively generates a uniform electric field.
2. The vector nature of the electric field was experimentally verified using the water-based mapping system. The ratio of the electric field measured along the diagonal to that measured along the horizontal showed strong agreement with the theoretical cosine relationship, with only a 4,8 % relative error. This result provides direct experimental support for understanding the vector components in electric fields.
3. The path independence of electric potential difference was investigated and confirmed within experimental uncertainty using the water medium. Regarding conservative behavior of electric potential, the low difference in direct potential measurements between two distinct paths confirms the path-independence of electric potential. Although the summation of small segments produced larger

deviations, this aspect of the experiment served as a critical pedagogical opportunity for students to explore measurement uncertainties and sources of systematic error.

Overall, this experimental material allows students to experience abstract concepts in electricity within a concrete learning environment, helping to address well-documented misconceptions in the literature [7]. The apparatus emphasizes the importance of low-cost and visually accessible laboratory tools in physics education and provides a valuable contribution to both secondary and undergraduate instruction by enabling learners to understand fundamental principles not merely through formulas, but through direct observation and measurement [6, 11].

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