REVIEW

A Detailed Review of pH and its Applications

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Abstract: The pH of a solution is an important measure of how acidic or alkaline it is. It shows the concentration of hydrogen ions in the solution through a negative logarithm. This measurement gives insight into how a substance behaves chemically. Scientists use a pH electrode to get accurate pH readings, which provides reliable measurements for different tests. pH is a key concept in chemistry and is relevant in many scientific fields, including biochemistry, biology, physics, medicine, agriculture, and environmental science. Keeping the right pH level is crucial in many industries, especially in chemical manufacturing, food production, and environmental protection, as it can directly affect the quality of lab results. Even small changes in pH can lead to major differences in the accuracy of analytical outcomes. This is particularly important when following strict guidelines in pharmacopoeias or conducting research using databases like Scopus and PubMed, where data accuracy is vital. This article explains the essential aspects needed to use pH measurement effectively in analysis. It provides a detailed look at other factors necessary for practical testing. Additionally, it highlights the various ways pH measurements are used, showing their importance across different scientific and industrial areas.

Keywords: electrode, buffer solution, pH indicators

1 Introduction

The pH value indicates the level of acidity or alkalinity present in a solution. In the context of Pharmacopoeia, specific standards and limits for pH are established for substances where pH is essential for stability or physiological suitability. The pH is determined at $25^\circ \pm 2^\circ$ unless stated in the individual monograph [1].

pH is defined for compendial purposes as the value obtained using an adequately calibrated potentiometric sensor and measuring system, traditionally known as a "pH meter" [2]. Contemporary measurement systems can integrate pH sensors and digitally transmit the pH signal to external devices, including computers, Data Acquisition Systems (DAS), Distributed Control Systems (DCS), Programmable Logic Controllers (PLCs), terminals, or other devices governed by microprocessors.

The negative logarithm of the hydrogen ion activity to base 10 is considered pH, represented as -log10[a+]. In this context, a+ denotes the activity of hydrogen ions (H+) or hydronium ions (H3O+), and the activity of hydrogen ions is a close approximation of their concentration.

The practical pH scale is characterized as follows:

$$pH = pHS + [(E - ES)/k] \tag{1}$$

where,
E = measured potential where the galvanic cell contains the solution under test (pH);
ES = measured potential where the galvanic cell contains the appropriate buffer solution for calibration (pHS);
k = change in potential/unit change in pH and is derived from the Nernst equation (as follows):

$$k \ = log_e(10) \times (RT/nF) \tag{2}$$

where,
R = 8.314 J/mole/$^\circ$K;
T = temperature ($^\circ$K);

n = moles/half-reaction;
F = Faraday constant, 96485 C/mole.

The resulting equation is [$0.05916 + 0.0001984(T - 25^{\circ})$] volts at temperature T. Values of k from 15°–35° are provided in Table 1.

Table 1 Values of k at different temperatures

T (°C)	k(V)
15.00	0.05718
20.00	0.05817
25.00	0.05916
30.00	0.06016
35.00	0.06115

The equation presented can be utilized to ascertain the values of k at various temperatures. For practical purposes, k values are determined using pH sensor calibration [3].

2 pH

A potentiometric method can accurately determine a solution's pH level. It combines a pH meter, a reference electrode, and a glass electrode. These electrodes are available in analogue and digital formats, allowing measurement flexibility [4].

Adhere to the manufacturer's instructions to ensure precision when operating the pH meter. Begin by calibrating the device using a primary standard, specifically buffer solution D. This is essential for obtaining the correct pH value corresponding to the temperature of the tested solution.

To establish a reliable pH scale, incorporate an additional reference buffer solution, such as buffer solution A, buffer solution E, or buffer solution G. This step is vital for enhancing the accuracy of your measurements. It is also recommended to verify the calibration by testing a third buffer solution that possesses an intermediate pH level [5].

When examining the electrodes, it is essential to confirm that the pH measurement obtained from the intermediate solution does not deviate more than 0.05 pH units or at least 0.003 volts from the corresponding value indicated in Table 2 [6]. This verification step ensures the reliability and integrity of the pH readings obtained during your experiments. With this, we have addressed key considerations regarding pH measurement and the use of buffer solutions.

(1) If the pH measurement from the intermediate solution falls outside the acceptable range, immediate corrective action should be taken to recalibrate the pH meter or adjust the solution accordingly. This may involve recalibrating the meter using fresh buffer standards and re-assessing the solution's pH to ensure accuracy.
(2) Failing to calibrate the pH meter correctly before use can lead to significant measurement errors, which may compromise experimental integrity, result in invalid data, and ultimately affect downstream processes and conclusions.
(3) We explored the distinctions among the various buffer solutions (A, D, E, and G), including their pH ranges, ionic strengths, and specific applications. Each buffer has unique characteristics that make it suitable for particular experimental conditions, and understanding when to use each is crucial for maintaining pH stability in diverse chemical analyses and biological experiments [7].

2.1 Approximate pH of Solutions

Determine the approximate pH using a pH indicator strip. Alternatively, pH indicators like those described in Table 2 can be used.

The pH measurement system requires three main components to measure pH levels accurately. First, there is a measuring electrode, typically a glass electrode sensitive to hydrogen-ion activity, although other types of electrodes are also possible. Second, there is also a reference electrode, for instance, a silver-silver chloride electrode. Finally, the high input impedance of the pH sensor can be measured using a voltage measurement system with an input resistance [8].

These components can be configured in different ways. The measuring and reference electrodes may be distinct or unified, and the voltage measurement system can function independently or be incorporated within the pH sensor. Furthermore, it is essential to measure the

Table 2 pH of solutions

Nature of Solution	pH	Indicator
Alkaline	> 8	Red litmus paper R
Slightly Alkaline	8 – 10	Phenolphthalein solution R Thymol blue solution R
Strongly Alkaline	> 10	Phenolphthalein paper R Thymol blue solution R
Neutral	6 – 8	Methyl red Solution R Phenol red solution R
Acid	< 6	Methyl red Solution R Bromothymol blue solution R1
Slightly Acid	4 – 6	Methyl red Solution R Bromocresol green solution R
Strongly Acid	< 4	Congo red paper R

effect of temperature on pH measurements. This can be accomplished by utilizing an integrated temperature sensor within the pH sensor or employing an external temperature measurement device. Overall, the pH measurement system is crucial for determining acidity or alkalinity levels in a given substance and requires careful calibration and maintenance to ensure accurate results [1, 3]. It outlines the specifications and acceptable deviation levels for pH measurements, particularly emphasizing the criteria of 0.05 pH units and 0.003 volts.

2.2 Requirements

A pH calibration with two points or more must be possible with the pH measurement system. The Calibration section provides a comprehensive overview of the accuracy of the pH measurement system. The pH measurement system should have a resolution of at least 0.01 pH. The instrument must be able to temperature-compensate the pH sensor readings to accurately convert the millivolt signal into pH units across various temperatures [9]. This can be accomplished either through the automatic functionality of an integrated temperature device within the sensor system or by manually inputting the sample temperature into the measurement system. The temperature measurement system's accuracy should be within $\pm1^\circ$, and its resolution should be at least 0.1°. Laboratory pH measurements are generally performed at $25 \pm 2^\circ$ unless indicated in the specific monograph or elsewhere. Temperatures outside this specified range may be permissible if preparing samples at different temperatures is more convenient. Non-laboratory measurements can encompass test samples within process pipes, vessels, tanks, and other unconventional processing environments. It is essential to recognize that the definitions of pH, the pH scale, and the values designated for buffer solutions used in calibration are intended to create a functional and operational framework for comparing laboratory results. The recorded pH values may not precisely align with those derived from the pH definition (pH = -log10 [aH+]). They remain closely associated with the behavior of hydrogen ions in aqueous solutions. When calibrating a pH measurement system with an aqueous buffer and applying it to non-aqueous systems, it is crucial to consider several factors. Several factors can influence the accuracy of pH measurements, including the liquid-junction potential, a significant source of error that can lead to variations of approximately one pH unit. This potential arises at the interface between different electrolyte solutions within the measuring system. Additionally, the dielectric constant of the medium plays a crucial role, as it affects the behaviour of ions in the solution and can alter the outcomes of pH measurements. Technologies and solutions aimed at minimizing errors in pH measurements, particularly those arising from liquid junction potential and the dielectric constant in non-aqueous systems, include the use of specialized double-junction electrodes, the selection of appropriate filling solutions compatible with the sample, the implementation of flowing reference junctions, and the application of non-aqueous reference buffers when conducting measurements in non-aqueous solvents [10]. These carefully designed measures aim to effectively minimize the potential difference at the liquid junction interface, thereby ensuring precise and reliable readings across a diverse array of sample types. By addressing potential discrepancies, these strategies enhance the accuracy and consistency of the measurements obtained.

Moreover, the ionisation constant of the measured acid or base also contributes to the overall accuracy. This constant indicates how readily the compound dissociates into ions in solution, affecting the concentration of hydrogen ions, a key determinant of pH.

Finally, there can be notable implications for the glass electrode's response to hydrogen ions. The electrode's sensitivity and selectivity depend on its composition and conditioning, which can influence how accurately it detects changes in hydrogen ion concentration. Understanding these factors is essential for achieving reliable and precise pH readings in various applications. Consequently, the values derived from only partially aqueous solutions should be considered apparent pH values [3, 11].

3 Calibration and Measurements

In the context of calibration and measurement conditions, all measurements should be performed at the same temperature utilized for calibration, typically within the range of 20°C to 25°C, with a permissible variation of ±2.5°C, unless otherwise stated in the monograph. It is crucial to follow the manufacturer's guidelines for temperature adjustment [12].

Calibration entails the assessment of both the slope (e.g. 95-105 per cent) and the offset of the measurement system. Many commercial instruments are equipped with a "self-test" or "start-up test" feature that evaluates parameters like slope and asymmetry potential, measuring the outcomes against the specifications set by the manufacturer. The calibration procedure necessitates using a minimum of two buffer solutions that are meticulously chosen to ensure that the anticipated pH value of the sample lies within the range of the pH values of the buffer solutions. The pH range must be a minimum of two units. Furthermore, when assessing the pH of an intermediate buffer solution, the measurement should not vary by more than 0.05 pH units from the anticipated value for that particular solution [13]. When choosing reference buffer solutions, opting for commercially available certified reference materials validated for their accuracy and reliability is recommended. These solutions should be traceable to primary standards, ensuring quality and consistency. It is also essential to regularly calibrate the reference buffer solutions to maintain their accuracy and reliability in various applications [14].

Calibrating the measurement system regularly is essential to ensure accurate pH measurements. It is recommended that the system be calibrated daily or before each series of measurements to maintain accuracy [15]. It is essential to maintain consistency with the conditions employed for the reference buffer solutions when submerging the electrodes in the solution under examination. This will help in obtaining reliable readings. For suspensions, emulsions, or solutions that possess non-aqueous or partially non-aqueous properties, it is essential to recognize that pH measurements should be regarded as estimates of the actual value when taken from a system calibrated in the manner previously outlined [16]. It is essential to use suitable electrodes for pH measurements of such mixtures to ensure accuracy [12].

Calibrating pH measurement systems can be complex due to their nature and operation variations. To initiate the calibration process, it is recommended to examine the electrodes, particularly the reference and electrolyte levels, if relevant. Should it be required, restore the electrolyte supply and follow any additional precautions outlined by the instrument manufacturers and electrodes [17]. Following these general principles will contribute to achieving accurate pH measurements. It is essential to calibrate or verify the pH measurement system periodically. The frequency of calibration/verification should be based on the measurement system's historical performance, the pH measurement's criticality, the pH sensor's maintenance, and the measurement operation frequency [18]. The following procedure accommodates a range of calibration techniques, including two-point, multiple-point, and multiple-segment calibrations. Suppose the pH of the buffer is affected by ambient carbon dioxide. In that case, it is advisable to utilize recently boiled, purified water stored in a container specifically designed to reduce the absorption of carbon dioxide [19].

To properly calibrate the pH measurement system, it is advisable to select three buffer solutions from Table 4, ensuring the anticipated pH of the test material is encompassed within their range [3,6].

(1) Two buffers are used during calibration, while the third is reserved for verification. The value of the verification buffer must fall within the range of the two calibration buffers.

(2) Thoroughly rinse the pH sensor with water and then rinse it with the first buffer solution. Ensure the sensor is rinsed multiple times with water and buffer solution for accurate readings.

(3) Place the pH sensor in the first buffer solution at a temperature within the range specified in Table 4.

(4) If the measuring system does not include automatic temperature measurement and compensation, manually input the temperature and pH value of the buffer solution into the instrument for temperatures not listed in Table 4.

(5) Commence the calibration process using the first buffer as the manufacturer directs.

(6) Remove the pH sensor from the first buffer, rinse the electrode(s) with water, and then use the second buffer solution.

(7) Immerse the pH sensor in the second buffer at a temperature within the range specified in Table 4.

(8) If the measuring system does not include automatic temperature measurement and compensation, manually enter the buffer's temperature and the buffer solution's pH value at that

temperature into the instrument.

(9) Follow the manufacturer's guidelines for the subsequent buffer solution to finalize the two-point calibration sequence.

(10) After completing the two-point calibration process, it is crucial to ensure that the pH slope and offset fall within acceptable parameters. Typically, these parameters consist of a 90%–105% slope and an offset of 0 ± 30 mV (0.5 pH units at 25°). Depending on the pH instrumentation, the pH slope and offset can be determined through software or manual methods. If manual processes are employed, following the supplier's instructions for calculating the pH sensor slope/offset is crucial.

(11) If these parameters are not within acceptable limits, the sensor should be cleaned, replenished, serviced, or replaced as necessary. The two-point calibration process should then be repeated.

(12) Remove the pH sensor from the second buffer, thoroughly rinse it with water, and immerse it in the verification buffer.

(13) Submerge the pH sensor in the verification buffer at a temperature within the range specified in Table 2.

(14) If the measuring system does not feature automatic temperature measurement and compensation, manually input the temperature and pH value of the buffer solution at that temperature into the instrument.

(15) At the buffer solution temperature, the pH reading should fall within $\pm$ 0.05 pH of the value in Table 1.

3.1 Analog sensors

Analog sensors are designed to generate continuous signals that accurately represent a diverse array of physical quantities, such as speed, pressure, displacement, strain, and temperature. Although they may provide slightly more precise readings, they typically lack the extensive features found in their digital counterparts. These versatile sensors are employed across a multitude of industries, playing crucial roles in temperature monitoring, pressure sensing, sound detection, and acceleration measurements.

In the automotive sector, they are indispensable for monitoring engine temperatures, tire pressures, and even for ensuring the timely deployment of airbags. Meanwhile, in healthcare, analog sensors are integral to a variety of life-saving devices, including electrocardiograms (ECGs), blood pressure monitors, and pulse oximeters, where they contribute to the accurate tracking of vital signs and patient health.

3.2 Digital sensors

Digital sensors play a crucial role in measuring various physical quantities and converting these measurements into digital signals. They produce discrete outputs, which are represented in binary code, predominantly consisting of ones and zeros (1s and 0s). These sensors often incorporate sophisticated algorithms and advanced digital processing techniques, frequently requiring analogue-to-digital converters (ADCs) to transform analog inputs into a digital format suitable for processing.

A prime example of digital sensors is temperature sensors, which are designed to interpret physical temperature changes through analog input signals. The versatility of digital sensors enables their application across numerous fields, including environmental monitoring, where they track changes in atmospheric conditions; robotics, where they facilitate precise movements and actions; and consumer electronics, enhancing user experiences through responsive functionalities [20, 21]. Comparison of analog and digital sensors are mentioned in Table 3.

Digital sensors utilize a variety of sophisticated methods for data storage, enhancing their functionality and accuracy. One notable feature in contemporary devices is "Automated Temperature Compensation," which refers to the capability of a device to automatically adjust its readings or operations based on the ambient temperature. This process typically involves the integration of a built-in temperature sensor that continuously monitors the environment, applying mathematical corrections to the output. As a result, users can achieve precise measurements, even when temperature conditions fluctuate [22].

3.3 Automated Temperature Compensation (ATC)

A prime illustration of this feature can be found in pH meters, which incorporate "Automatic Temperature Compensation (ATC)." This function dramatically enhances the accuracy of pH readings by adjusting them according to the temperature of the solution being tested [23].

Table 3 Difference between Analog Sensors and Digital Sensors

Sr.	Factors	Analog Sensors	Digital Sensors
1.	Waves	Utilization of sine wave patterns	Adoption of square wave patterns
2.	Signal	Constant signals obtained from measurements are common	Digital modulation signals are represented at discrete intervals
3.	Bandwidth	These sensors typically operate in real-time, thereby utilizing a reduced bandwidth	Given the potential challenges in real-time signal processing, a higher bandwidth is often required
4.	Noise Response	The accuracy of these sensors may be influenced by noise levels	Digital sensors generally exhibit a more robust performance against noise compared to analog sensors
5.	Portability	Analog sensors are recognized for their portability	Conversely, digital sensors may not offer the same level of portability
6.	Data Transmissions	Transmission of data may be susceptible to noise interference	Digital signals, however, are often able to maintain integrity despite noise during transmission
7.	Power Requirements	Analog sensors are known to consume a considerable amount of power	In contrast, digital sensors tend to operate with minimal power consumption
8.	Flexibility	Analog sensors may present certain limitations in flexibility	In contrast, digital hardware is known for its considerable flexibility
9.	Common Errors	Analog sensors can be associated with observable errors	Digital sensors are generally free from such observational errors
10.	Memory	Analog sensors store information as wave signals	Digital sensors stores information as binary bit

3.4 Advantages of Automated Temperature Compensation

ATC in modern devices are significant. This innovation not only ensures accurate measurements irrespective of temperature variations but also enhances reliability and consistency in results. The capacity for real-time adjustments, comprehensive data logging, and alerts for exceeding temperature thresholds facilitates efficient monitoring and analysis. These features are especially vital in applications where precise temperature control is essential, leading to minimized errors and improved outcomes in various scientific and industrial fields [24].

3.5 Limitations of Automatic Temperature Compensation

3.5.1 Sample-Specific Temperature Effects

Automatic Temperature Compensation (ATC) is fundamentally designed to counteract the typical temperature-responsive behavior exhibited by electrodes. However, it frequently encounters limitations when attempting to accommodate the distinct temperature sensitivities inherent to individual samples. This inherent shortcoming can lead to substantial discrepancies in the accuracy of pH measurements, particularly in instances where the properties of a sample exhibit marked variations in response to temperature shifts. The nuanced interplay of temperature and sample characteristics underscores the critical need for careful consideration in pH assessment.

3.5.2 Calibration Dependency

The efficacy of ATC is intricately linked to the calibration process, which must be meticulously conducted at a defined temperature to guarantee optimal precision. Should subsequent measurements diverge significantly from this established calibration benchmark, the potential for inaccuracies rises dramatically. Such deviations can culminate in erroneous results that not only compromise the integrity and reliability of the collected data but also provoke serious concerns among researchers and practitioners committed to producing valid findings.

3.5.3 Non-Linear Temperature Effects

In certain samples, pH values exhibit complex non-linear responses as the temperature fluctuates, presenting a formidable challenge that conventional ATC algorithms often struggle to effectively address. This intricate behavior necessitates the implementation of more sophisticated methodologies to accurately assess pH variations in response to shifting thermal conditions. Consequently, this highlights the pressing need for innovative approaches in analytical practices that can adeptly navigate these complexities and enhance measurement reliability.

3.5.4 Potential for Inaccurate Readings in Extreme Temperatures

In extreme thermal environments—whether teetering on the edge of blistering heat or plunged into the frigid cold—the reliability of ATC can be profoundly compromised. The performance of both the electrode and the measuring device plays a pivotal role in determining the accuracy of readings taken under such challenging conditions. Recognizing and understanding the inherent limitations of ATC in these scenarios is crucial for obtaining trustworthy measurements. This comprehension is essential not only for ensuring the validity of scientific conclusions but also for maintaining the accuracy and credibility of research findings in the face of extreme temperature challenges.

3.6 Operation of an Instrument

When preparing test samples, purified water is essential unless the specific monograph states otherwise. Additionally, Nernst temperature compensation—whether automated or manual—should be incorporated into all measurement processes to ensure accuracy [25].

When creating the test material, follow the procedural guidelines or the monograph carefully. Suppose the sample's pH may be influenced by environmental carbon dioxide. In that case, it is recommended to use purified water that has been recently boiled and stored in a container that prevents CO2 ingress [26].

Before measurements, the pH sensor must be thoroughly cleaned using purified water and several test samples. The sensor must be immersed in the sample material to ensure accurate readings, allowing enough time for the temperature and pH levels to stabilize before conducting any measurements [27]. In cases where equipment deficiencies are suspected, diagnostic functions, including the measurement of glass or reference electrode resistance, may help identify any problems.

It is recommended to consult the electrode supplier for suitable diagnostic tools to guarantee the optimal performance of the electrodes if needed. Indicators and test papers could be appropriate if approximate pH values satisfy requirements. Further information on reagents, indicators, and solutions can be found in the designated section. Standard buffer solutions are commonly utilized for compendial tests and assays. The solutions section, specifically the buffer solutions subsection, offers comprehensive analyses of buffers and the formulation of standard buffer solutions. It is important to note that the pH calibration buffers in Table 4 should not be replaced by the information provided in this section [3, 28].

Table 4 The reference buffer solutions pH values at various temperatures recommended to choose three buffer solutions in order to calibrate the pH measurement device

T (°C)	Potassium tetraoxalate 0.05 M	Potassiumm hydrogenn tartrate saturated at 25 °C	Potassiumm dihydrogen citrate 0.05 M	Potassiumm hydrogen phthalatee 0.05 M	Potassium dihydrogen phosphate 0.025 M+ Disodium hydrogen phosphate 0.025 M	Potassium dihydrogen phosphate 0.0087 M + Disodium hydrogen phosphate 0.0303 M	Disodium tetrabo rate 0.01 M	Sodium carbonate 0.025 M + Sodium bicarbonate 0.025 M	Calcium hydroxide saturated at 25°C.
	C4H3KO8, 2H2O	C4H5KO6	C6H7KO7	C8H5KO4	KH2PO4 + Na2HPO4	KH2PO4+ Na2HPO4	Na2B4O7, 10H2O	Na2CO3+ NaHCO3	Ca(OH)2
15	1.67	-	3.8	4	6.9	7.45	9.28	10.12	12.81
20	1.68	-	3.79	4	6.88	7.43	9.23	10.06	12.63
25	1.68	3.56	3.78	4.01	6.87	7.41	9.18	10.01	12.45
30	1.68	3.55	3.77	4.01	6.85	7.4	9.14	9.97	12.29
35	1.69	3.55	3.76	4.02	6.84	7.39	9.1	9.93	12.13
$\frac{\Delta pH^{(1)}}{\Delta t}$	0.001	-0.0014	-0.0022	0.0012	-0.0028	-0.0028	-0.0082	-0.0096	-0.0034

Note: $^{(1)}$ pH variation per degree Celsius

3.7 Safety and Precautions

(1) Among the dangers associated with working with chemicals and technological devices are chemical leaks and electrical shocks. Protect yourself from these and other hazards by donning the appropriate safety equipment, such as goggles, gloves, and a lab coat [29].

(2) Many chemicals used in industrial processes can release hazardous vapours that are unhealthy to breathe in. To prevent respiratory disorders and other health problems, use your pH meter in an area with enough ventilation [30]. If you're working in a tiny space or lab, use a fume hood or another type of air filtering equipment to assist in keeping the air clean [31].

(3) Due to variations in glass electrode resistance, pH readings are temperature-sensitive. Hence, keep the pH meter out of direct sunlight to avoid temperature fluctuations [32].

(4) A pH meter needs to be calibrated regularly to work properly. A pH meter must be calibrated to measure pH precisely and accurately [33]. Inaccurate readings from a pH meter that isn't routinely calibrated may result in incorrect diagnoses or decisions [34].

(5) When not in use, the pH probe is always stored in a potassium chloride (KCl) solution to

preserve its internal chemistry and stop the solution inside the probe from leaking or evaporating. Since KCl is pH-neutral and doesn't alter the pH of the solution being tested, it's a good source of ions that finish the circuit in a pH meter [13, 33].

(6) Most used digital pH meters are costly devices that need to be handled carefully. Never drop the pH meter; always grab it by the handle. Never touch the sensor with your bare hands or any other object to avoid damaging it [35].

4 Applications of pH Measurement

4.1 In Biomedical Engineering

In biomedicine, pH is crucial in characterizing the acidity or basicity of various biological entities, including tissues, organs, and blood [36]. The intracellular pH is critical, as it influences many cellular functions, enzymatic reactions, and tissue processes, such as muscle contraction, endocytosis, and ion transport [37]. Monitoring changes in intracellular pH is vital for understanding the pathways through which cells internalize substances [38]. Fluctuations in intracellular pH can significantly affect the nervous system, affecting synaptic transmission, neuronal excitability, and cell communication via gap junctions. Furthermore, abnormal pH levels have been associated with various diseases, including malignant tumors and Alzheimer's, as they can compromise cellular function, growth, and division [39]. In wound monitoring, the research conducted by Schneider et al. highlights the significance of pH as a reliable indicator of a wound's condition. PH measurements can guide clinical assessments and treatment strategies by providing essential insights into bacterial contamination and the healing process [40].

A pH meter is a sophisticated equipment comprising several components, including a pH transducer, a pCO2 transducer, and a thermostat, all of which operate independently within a trolley that houses a calibrating gas system for pCO2 measurements [41]. The relationship between pH and emf is linear; this relationship is detected using an electronic millivolt meter calibrated in pH units [13, 42]. When carbon dioxide dissolves in aqueous sodium bicarbonate (NaHCO3) solution, it lowers the pH, where a tenfold increase in pCO2 results in a reduction of 1.0 pH unit. Notably, over a pCO2 range from 1.5% to 100%, there is a clear linear relationship when plotting the logarithm of pCO2 against pH. The glass electrode is encased in a jacket filled with electrolytes, connecting with the reference electrode. Carbon dioxide diffuses across the membrane until the partial pressures of CO2 in the sample and the NaHCO3 solution reach equilibrium, leading to pH changes that accurately reflect the pCO2 level in the sample [43].

Innovatively, Nikolai et al. have created a pH-sensitive, water-soluble fluorescent nano micellar sensor specifically designed for biomedical applications [44]. This cutting-edge sensor showcases exceptional sensitivity, featuring highly soluble fluorescent micelles. The pH probe operates in aqueous environments and can penetrate and internalize within cells. It has been engineered to effectively target the acidic microenvironments commonly found in tumor cells, allowing for efficient absorption by cancer cells and ensuring a high cellular uptake. This unique targeting capability positions the probe as a promising tool for cancer diagnostics and therapy [45]. The successful uptake of the pH probe into these malignant cells enhances our understanding of their biochemical environment and paves the way for advancements in diagnostic imaging techniques [46]. Furthermore, this capability holds significant promise for developing targeted therapeutic interventions in the field of oncology, potentially leading to more precise and effective treatment options for patients [47]. Additionally, it has demonstrated cell specificity and a markedly more excellent photostability than a pure organic dye label, such as BODIPY.

A pH sensor made of polymethylmethacrylate (PMMA) optical fibres has been developed for on-body monitoring in biological fluids. This sensor, whose detection mechanism is based on evanescent wave absorption in a thin film applied to the fibre core, has been used to monitor biological fluids, especially in wound healing [48].

4.2 In Industrial Process

The measurement of pH plays a vital role in understanding the chemical properties of substances and serves as a foundational step in regulating chemical reactions. In recent years, the application of pH measurement has expanded significantly, reaching various sectors, including the chemical industry, public organizations, and agricultural and fishery industries. Furthermore, it is integral to sectors involved in water management, where precise pH assessments are crucial for maintaining product quality.

4.2.1 Pharmaceuticals

pH is essential in creating and distributing medications in the pharmaceutical sector. A drug's solubility, durability, and body absorption are all impacted by its pH level [49]. By adjusting and monitoring the pH levels in their labs, pharmaceutical firms can regulate the rate at which the drug is released and improve its effectiveness. pH is also crucial when developing injectable medications to minimise pain, discomfort, or damage to tissues at the injection site [50]. By modifying the pH, companies can enhance the drug's stability and lower the chances of adverse side effects. For example, many oral drugs require certain pH levels in the stomach to be absorbed effectively. Aspirin is an acidic drug that dissolves in the stomach's acidic environment. To be compatible with the body's tissues, drug delivery techniques such as transdermal patches or eye drops must maintain a neutral pH [51].

4.2.2 Automotive Industries

From coolant systems to battery maintenance, pH affects many facets of the automotive sector. Measuring the electrolyte's pH is essential to maintain the battery's longevity and performance [52]. A pH imbalance may indicate battery deterioration or maintenance requirements. Vehicle coolant systems depend on pH readings to guarantee effective heat transfer and stop corrosion. The coolant can prevent rust and scale formation by keeping the pH range within the proper range, safeguarding the cooling system and engine parts [53]. A key example is keeping an eye on the pH level of the coolant used in engine testing and production line operations to make sure it stays within the designated range to prevent corrosion and optimize engine performance; if the pH is too acidic or too alkaline, it can damage engine components, potentially leading to quality issues and recalls. In the automotive industry, pH level monitoring is essential for managing the quality of cooling systems, especially in the manufacturing process where coolant solutions are used to maintain optimal engine temperatures. A crucial aspect of maintaining engine integrity lies in the careful monitoring of the pH levels of the coolant utilized during engine testing and production line operations. Keeping the pH within the specified range is vital to prevent corrosion and ensure optimal engine performance. If the coolant becomes too acidic or too alkaline, it can lead to severe damage to engine components, which may result in quality control issues and costly recalls. In the automotive industry, diligent pH level monitoring is indispensable for managing the quality of cooling systems. This is particularly important during the manufacturing process, where precise coolant solutions are crucial for regulating engine temperatures and safeguarding against overheating. Maintaining the ideal pH balance is integral to extending the lifespan and reliability of engine systems [54].

4.2.3 Food and Beverage

In food processing, the effectiveness of high-pressure treatments is closely linked to the changes in pH levels induced by applying pressure. Researchers conducted in situ measurements of pH levels in selected liquid foods at 25°C while subjecting them to elevated hydrostatic pressures, reaching as high as 800 MPa [55]. Utilizing a high-pressure pH sensor that had undergone thorough validation, the results revealed a consistent trend: all tested food and water samples exhibited increased acidity as pressure escalated. When producing any food or beverage product, it is crucial to monitor the pH levels [56]. Consumers may suffer dental damage if the water used to make beverages is excessively acidic. Businesses that produce food must also monitor pH levels to guarantee that their goods are high-quality and safe to consume. For instance, pork with a pH of 5.6 to 6.0 suggests the pig was correctly raised; a lower pH value indicates the pig may have had a stressful upbringing. Additionally, to prevent bacterial growth, a meat product like salami should have a pH of less than 5.3 [53, 57].

The study explores the distinction between traditional industries like food processing and modern, high-tech industries like nanotechnology. pH measurements in food processing ensure quality control, safety, taste, texture, and shelf life. Nanotechnology can detect pathogens, extend shelf life, improve food quality, and reduce food wastage by enhancing nutrient bioavailability and production [58, 59].

4.2.4 Electricity and Electrochemistry

The electricity, electrochemistry, and pH measurements are fundamental throughout several approaches, together with metallic floor plating, etching, and the assembly of batteries. The pH management in a plating solution plays a widespread role in figuring out the final look of the plated surface. Inadequate pH regulation can bring about an end that is liable to peeling and fails to achieve the favored color and luster. Furthermore, the anodic oxidation procedure used to coat cooking utensils is based on preserving precise pH tiers inside the processing method to produce a movie-like layer reminiscent of that on aluminum items [53, 60].

4.2.5 Textile and Dyeing Industry

Ensuring proper pH levels is crucial for accurate product testing. The pH of the dye bath can significantly affect both the durability of the dye and the speed of dye processing [61]. Recent advancements suggest that integrating a pH indicator into a nylon nanofibrous structure could be achieved by adding dye to the polymer solution before an electro-spinning process. This innovative approach can also lead to the development of textile pH sensors that could open up a wide array of capacity programs throughout numerous fields [62].

4.2.6 Wastewater Treatment

Heavy metals, organic compounds, and other harmful substances are eliminated during wastewater treatment; chemicals must be added to the water to change the pH levels and separate the dissolved waste from the liquid. To ensure that water can thoroughly pass on to the subsequent level of remedy and that they have easy, secure water at the quit of the cleansing technique, managers of facilities that method sewage or recycle water utilized in manufacturing should keep a watch on pH degrees [63]. This issue of pH measurement is particularly pertinent in industries that include paper and pulp production, in which it is regularly monitored more rigorously than in other sectors. This is because of the character of wastewater produced at pulp and paper centers, which contains effluents from various tactics such as pulping, bleaching, paper manufacturing, and recycling [64]. Treating this wastewater entails a complex process where suspended solids are separated and settled in a precipitation tank, aided by flocculation dealers. Here, maintaining an appropriate pH degree is critical for minimizing chemical utilization and stopping the gadget's corrosion in the treatment manner [43]. At the Perundurai Common Effluent Treatment Plant (PCETP), the predominant type of wastewater encountered is alkali waste, characterized by its elevated pH levels. To safeguard the delicate microbial life essential for effective biological treatment and to reduce the dependency on chemical additives, hydrochloric acid (HCl) is judiciously introduced. This precise addition helps maintain the pH within a controlled range of 7.5 to 7.8, ensuring an optimal environment for the microbes to thrive while effectively managing the treatment process [65].

4.3 In Microfluidics

The process of detecting the acidity or alkalinity (pH level) of minuscule volumes of liquid within a microfluidic chip is referred to as pH monitoring. This sophisticated technique typically employs integrated sensors that accurately identify pH variations, enabling the real-time examination of microenvironments. Maintaining precise pH levels is crucial for the successful cultivation of cells and the dynamics of biochemical reactions. Common methodologies for pH monitoring include the use of optical pH indicators, ion-selective field-effect transistors (ISFETs), and colorimetric assays. The selection of a particular method is guided by the required sensitivity and the specific characteristics of the microfluidic chip utilized, thereby ensuring optimal performance in various applications [66].

Microfluidics seeks to consolidate various laboratory functions onto a singular, compact microfluidic chip, paving the way for innovative applications in the fields of physics and biomedicine. This remarkable miniaturization not only enhances portability but also significantly reduces costs while facilitating intricate studies at the cellular scale. Researchers are increasingly drawn to the potential of microfluidics for cell culture investigations, as it allows for real-time growth monitoring and observation of cellular behaviours in controlled environments.

Despite these advantages, the isolation of the chip from the external environment poses challenges for direct monitoring of the microenvironment, making the measurement of pH levels particularly vital. This text explores various methods for achieving pH monitoring within microfluidic devices and highlights the integration of solid-state sensors designed for accurate pH measurements in these advanced systems. Such advancements promise to enhance our ability to conduct precise and meaningful analyses in complex biological processes [67].

pH monitoring within microfluidic systems plays a crucial role across various applications, including cell culture, drug delivery, organ-on-a-chip devices, biomolecular analysis, and environmental monitoring. By meticulously regulating pH levels, these systems ensure optimal conditions for cell growth, enhance the effectiveness of drug formulations, support the proper functioning of organ simulations, and facilitate accurate assessments of environmental samples. This precise control is essential for advancing research and development in biomedical science and environmental sustainability [68].

5 Conclusions

In pH operations, ensuring accuracy and precision is of utmost importance. Achieving this requires a meticulous approach to defining the analysis requirements, adhering to stringent compliance protocols, and minimizing the impact of pH fluctuations on the overall uncertainty of the analysis. By engaging in thoughtful calibration, evaluating repeatability, and rigorously assessing accuracy, we can ascertain the ideal minimum quantity of solution needed to obtain optimal results.

To clearly define the analysis requirements, it is essential to establish specific objectives for the analysis, identify the relevant parameters to be measured, and outline the acceptable ranges for each parameter. This involves consulting standard methods and guidelines, as well as communicating with all stakeholders involved to ensure a comprehensive understanding of the project goals.

Reducing the influence of pH on overall analysis uncertainty entails implementing several strategies, such as utilizing high-quality buffers to stabilize pH levels, conducting regular maintenance and calibration of pH meters, and controlling environmental variables that may cause fluctuations in pH measurement.

Assessing repeatability in pH measurements can be effectively achieved through multiple methods, including performing a series of repeated measurements under identical conditions to calculate the standard deviation. Additionally, employing control charts to monitor variations over time and conducting method validation studies can further enhance the understanding of repeatability and reliability in pH analysis.

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Ritu Tiwari: Conceptualization; Supervision; Methodology; Writing Original Draft; Review and Editing.

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Conflict of Interests

All authors declare that they have no conflicts of interest.

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