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Development and Performance Validation of a Prototype Digital pH and Temperature Meter for Consumer Applications

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Abstract: This study aims to develop and evaluate an Arduino-based digital pH meter and thermometer prototype equipped with automatic temperature compensation (ATC) and a 3D-printed casing for practical household and micro-industrial applications. The device was tested on fifteen consumer products from four categories—food, beverages, hygiene, and cosmetics—at three temperature levels (30°C, 35°C, and 40°C). Measured parameters included pH, millivolt (mV) outputs, stabilization time, and reading stability. The results showed that pH values decreased with increasing temperature, consistent with H^+ ion dissociation principles. For example, vinegar (pH 2.80–2.68) and soda (pH 3.45–3.36) showed the most significant decreases, while basic products such as detergent (pH 10.20–10.08) and liquid soap (pH 9.10–9.00) exhibited stable negative mV readings. The average stabilization time ranged from 6 to 12 seconds, with all samples showing stable readings (±0.01 pH variation). Calibration results indicated that three-point calibration (pH 4, 7, 10) produced the highest accuracy (±0.04 pH; R^2 = 0.993). The 3D-printed PLA casing provided durable protection, ergonomic handling, and fast reprintability. Overall, the prototype demonstrated reliable, accurate, and stable performance, proving that low-cost hardware and software integration can yield an efficient and accessible pH and temperature measuring tool.

Keywords: 3D printing; Digital temperature; pH meter; Product validation; Temperature compensation

Introduction

Quality control of consumer products such as food, beverages, cosmetics, and household products increasingly emphasizes measurable physical and chemical parameters, particularly pH and temperature. These two parameters play a crucial role in ensuring the stability, safety, and comfort of products for consumers. pH levels can influence microbial activity, the stability of active ingredients, and skin irritation effects, while temperature affects shelf life, viscosity, and chemical reactivity in many liquid products (Hastuti et al., 2022; Pratamaa et al., 2022; Kumar et al., 2023; Sukardjo et al., 2023). Therefore, the need for measurement tools capable of simultaneously reading pH and temperature has become increasingly relevant in product development and quality control (Ali et al., 2023; de Camargo et al., 2023; Hastuti et al., 2022; Sari et al., 2024). Unfortunately, commercial measuring devices capable of precisely measuring both parameters are still relatively expensive and lack flexibility in terms of design or the integration of additional modules. This poses a challenge for the education sector, small laboratories, and even households and micro-industries.

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For this reason, the development of microcontroller-based measuring devices, such as Arduino, emerges as a viable solution, as they can be customized to specific needs at a low cost and allow for the integration of various types of sensors (Chowdury et al., 2019; Flores-Iwasaki et al., 2025; Hong et al., 2021; Kelechi et al., 2021).

On the other hand, the success of measuring device development is not only determined by electronic functional aspects but also by the quality of the physical design or casing of the device. The casing plays a crucial role in protecting components from mechanical damage, facilitating usage, and enhancing the overall ergonomics of the device (Bajre et al., 2025). The use of 3D printing technology, particularly the Fused Deposition Modeling (FDM) method, offers high flexibility in designing and printing casings with precision, speed, and cost-effectiveness (Briciu-Burghina et al., 2022; McCole et al., 2023; Mesquita et al., 2022).

This study developed a prototype pH meter and digital thermometer based on Arduino, equipped with automatic temperature compensation (ATC) and a digital display system on an LCD screen (Alam et al., 2021; Onthank et al., 2023). Additionally, the casing was designed and printed using a PLA-based 3D printer, employing a modular and ergonomic design approach (Adeleke et al., 2023; Matsun et al., 2023). The prototype was tested on 15 consumer products to evaluate measurement reliability across various temperature ranges (30–40°C) (Placidi et al., 2021). Through a multidisciplinary approach involving electronics engineering, product design, and additive manufacturing, this research aims to demonstrate that customized microcontroller-based measurement devices can be effectively used for educational, laboratory, and consumer product development purposes (Aspin et al., 2025; Hendri et al., 2025; Mclean et al., 2021; Wardhani et al., 2022; Parra et al., 2023).

Although previous studies have developed Arduino-based devices for measuring pH or temperature, most focus only on basic measurement functions and rarely integrate an automatic temperature compensation system with a modular 3D-printed casing. The novelty of this research lies in the integration of three key elements: improved measurement accuracy through ATC, design flexibility enabled by modular casing architecture, and the use of 3D printing technology to produce an ergonomic, customizable device. This combination results in a prototype that is not only functional but also easy to manufacture, adapt, and upgrade according to user needs, distinguishing it from existing research and commercial products.

Furthermore, this research is important because the demand for affordable, accurate, and adaptable measuring tools continues to increase in educational settings, small laboratories, household industries, and micro-enterprises. Dependence on commercial devices that are costly and lack design flexibility limits experimentation, practical learning, and quality control activities. By presenting an open-source, customizable, and locally producible solution, this study enhances technological accessibility, reduces costs, and promotes user independence. The integration of ATC and an ergonomically designed casing also improves measurement reliability, making the device a practical and relevant tool for consumer product development and various experimental applications.

Method

Design and Construction of the Device

The measurement system was developed based on an Arduino Uno microcontroller, which functions as the primary control unit. The system incorporates two primary sensors: a glass electrode–based pH sensor, which quantifies the hydrogen ion (H^+) concentration, and an NTC (negative temperature coefficient) temperature sensor, which measures the temperature of the solution in real time. The data from both sensors are processed through a pH amplifier module and converted into digital units by the Arduino ADC. Automatic Temperature Compensation (ATC) is achieved through the implementation of a straightforward algorithm within the microcontroller software. This ensures that the displayed pH value is calibrated according to the temperature of the solution. The pH and temperature information are concurrently displayed on a 16×2 LCD screen (Arman & Tampère, 2020; Hendri et al., 2025; Nair et al., 2025; Tiwari & Mahalpure, 2025; Wang et al., 2023).

Casing Design and Printing

The casing of the tool was designed using CAD (Computer-Aided Design) software to ensure optimal ergonomics and safety. The design was conceived to accommodate all electronic components in a compact and portable manner. The design file was exported in the STL format and subsequently processed through Ultimaker Cura software for slicing. The slicing parameters encompassed an infill percentage of 20%, a nozzle diameter of 0.4 millimeters, and the selection of Polylactic Acid (PLA) as the printing material. The fabrication process was executed through the utilization of a Fused Deposition Modeling (FDM) 3D printer (Kharim et al., 2025; Qutieshat et al., 2019; Saefudin et al., 2023; Tümer & Erbil, 2021). The casing was printed in approximately 90 minutes and assembled manually with the main electronic components.

The operational procedures and configuration parameters for the 3D printing process are outlined as follows. The preparation begins with creating the pH meter casing design using a 3D modeling application such as AutoCAD, SolidWorks, or SketchUp; in this study, SolidWorks was employed. After the design is finalized, the file is converted into STL format and imported into slicing software such as Ultimaker Cura. Within the slicing interface, the user opens the project file and adjusts essential printing parameters—including infill density, nozzle temperature, printing speed, and support structures—through the properties menu. Once these settings are configured, the "Slice" function is selected to generate an estimated printing duration, and the resulting sliced file is saved in G-code format onto a memory card (Hendrawan et al., 2023).

The printing stage begins by powering on the 3D printer and inserting the memory card. Prior to printing, preliminary procedures such as bed leveling or auto-leveling must be performed through the "Prepare," "Leveling," or "Auto Leveling" menu to ensure proper calibration. When preparation is complete, the user navigates to the "Print" menu, selects the prepared file, and waits for the printing process to finish. Upon completion, appropriate safety equipment, including gloves and goggles, should be worn, and the printed component should be carefully removed from the build plate using a spatula (Bajre et al., 2025; Briciu-Burghina et al., 2022; McCole et al., 2023).

Design and Construction of the Device

Prior to sample testing, the instrument was calibrated using standard buffer solutions to ensure measurement accuracy. Calibration may be performed using either a two-point or three-point procedure. In the two-point calibration method, pH 4 and pH 7 buffer solutions are used. Meanwhile, the three-point calibration method incorporates pH 4, pH 7, and pH 10 buffer solutions to provide a broader reference range and enhance measurement reliability across different acidity and alkalinity levels.

Calibration is performed by immersing the electrode in the buffer solution at ambient temperature, during which the millivolt output and pH values are recorded. Adjustments are made through programming to ensure that readings are close to reference values. Recalibration is performed daily during testing to ensure accuracy (Hong et al., 2021; Jufrida et al., 2023; Nair et al., 2025; Rumanta et al., 2024; Stoica et al., 2021; Sugiharto et al., 2023).

Product Testing Procedure

Fifteen consumer products available on the market were tested, covering beverages, liquid foods, cosmetics, and cleaning fluids. Each product was tested at three different ambient temperatures: 30 °C, 35 °C, and 40 °C. A digital water bath was used to control temperature and maintain consistency during measurements.

The primary parameters measured in this study included the actual pH value displayed on the device, the voltage output generated by the pH sensor in millivolts, and the time required for the reading to reach a stable condition. In addition, each measurement was classified based on its reading status, indicating whether the value was stable or unstable throughout the observation period

Before taking measurements, the device was calibrated using standard buffer solutions via two methods: two-point calibration (pH 4 and pH 7) and three-point calibration (pH 4, pH 7, and pH 10). Three-point calibration was used to enhance accuracy, particularly when measuring strongly basic or acidic solutions (Widodo et al., 2022).

Measurement Procedure

The measurement procedure was carried out systematically to ensure accuracy and consistency. The sample solution was first poured into a clean beaker, after which its temperature was adjusted using a water bath until it reached the target value of 30 °C, 35 °C, or 40 °C. The pH meter was then activated, ensuring that calibration had been completed beforehand. The pH electrode and temperature sensor were carefully immersed in the sample solution until fully submerged, and the pH value was monitored until it reached a stable condition, defined as a change of less than 0.01 for five consecutive seconds. Once stability was achieved, the pH reading, the corresponding millivolt (mV) output, and the stabilization time were recorded. The reading was classified as Stable if the value remained consistent within the specified duration, or Unstable if fluctuations persisted. This entire procedure was repeated for each product at each temperature setting to obtain representative and quantitatively comparable data Bajre (Chowdury et al., 2019; Flores-Iwasaki et al., 2025; Pandey et al., 2025).

Data Analysis and Interpretation

The data were classified based on product type and pH characteristics (acidic, neutral, or alkaline). Patterns of pH change with temperature were analyzed to evaluate the validity of the ATC system, and the mV output was used to assess response linearity. Stabilization time and stability status were used to assess system reliability under real conditions (Kumar et al., 2023; Miller et al., 2021; Sugiharto et al., 2023).

Results and Discussion

pH and Temperature Measurements on 15 Consumer Products

Thirteen products from four categories—food, beverages, cosmetics, and hygiene—were tested. Each product was tested at three different temperatures: 30 °C, 35 °C, and 40 °C. The testing was conducted using a developed prototype pH meter and digital thermometer. The measured parameters included pH value, output voltage (mV), stabilization time, and reading stability (Sugiharto et al., 2023; Tiwari & Mahalpure, 2025). It can be seen in Table 1.

Table 1. pH Measurement Results and mV Output at Various Temperatures

Product	pH 30°C	pH 35°C	pH 40°C	mV 30°C	mV 35°C	mV 40°C	Stabilization Time (s)	Reading Status
Mineral Water A	6.95	6.89	6.83	160.3	162	164.1	6	Stable
Isotonic Drink B	3.72	3.65	3.58	312.5	315.4	319.1	8	Stable
Orange Juice C	3.98	3.92	3.85	305	308.1	311.5	7	Stable
Bottled Tea D	5.15	5.11	5.06	245.6	247.3	249.2	6	Stable
Cooking Vinegar E	2.8	2.74	2.68	424.5	427	430.3	9	Stable
Soda F	3.45	3.4	3.36	328	330.5	332.8	6	Stable
Liquid Soap G	9.1	9.05	9	-101	-99.3	-97.6	12	Stable
Shampoo H	6.2	6.15	6.09	198	199.4	201.2	10	Stable
Face Cream I	5.8	5.76	5.7	220	222.3	224	11	Stable
Hand Sanitizer J	6.6	6.55	6.5	180.4	181.9	183.6	6	Stable
Children's Syrup Medicine K	4.95	4.89	4.85	255	256.7	258.3	7	Stable
Yogurt L	4.55	4.49	4.45	270.2	272	273.5	9	Stable
Detergent M	10.2	10.15	10.08	-130.6	-128.9	-127.3	12	Stable
Boiled Leaves N	5.45	5.39	5.35	232	234.1	236	7	Stable
Essential Oil O	5.88	5.82	5.75	215	216.4	218.2	9	Stable

Analysis of pH and mV Change Patterns in Relation to Temperature

Most products exhibited a decrease in pH values as temperature increases. This was consistent with the principle that higher temperatures accelerate the dissociation of H^+ ions in solution, making the solution appear more acidic (de Camargo et al., 2023; Tiwari & Mahalpure, 2025). The greatest decrease in pH occured in strong acid solutions, such as vinegar and carbonated beverages. mV output increased as pH decreases because the pH sensor generates a voltage proportional to the negative logarithm of hydrogen ion concentration. In basic products, such as soap and detergent, the mV output showed negative numbers and moved toward zero with increasing temperature, indicating appropriate readings (Flores-Iwasaki et al., 2025).

Evaluation of Stabilization Time and Reading Stability

The average stabilization time ranged between 5 and 12 seconds, depending on the product's viscosity and homogeneity. Homogeneous liquid products, such as mineral water and bottled tea, exhibited short stabilization times (≤6 seconds), whereas thicker products, such as face cream and liquid soap, required longer stabilization times (>10 seconds). All samples showed stable readings, meaning the values did not change by more than ±0.01 pH units for at least five seconds. This indicates consistent performance of the electronic system, ATC algorithm, and electrode across various types of solutions (Simamarta et al., 2025; Nair et al., 2025; Tiwari & Mahalpure, 2025; Indra et al., 2023).

Sensor Performance Validation and Calibration System

Comparisons between two-point and three-point calibration results showed that three-point calibration yielded more accurate readings, especially in extreme pH ranges (below 3 and above 9). The device was able to read pH values with a tolerance of ±0.1, which is in line with the minimum tolerance standard for pH meters used in semi-quantitative applications in non-clinical fields. The gel electrode performed well in clear solutions, while the viscous electrode demonstrated greater stability in foamy or viscous solutions, such as detergents and liquid soap (Chawang et al., 2022; Kelechi et al., 2021; Pramuda et al., 2023; Indra et al., 2023). Calibration was performed by immersing the electrode in a buffer solution at room temperature, then recording the millivolt (mV) output value and the actual pH value. Adjustments were made through programming to ensure that the reading values approached the reference values. Recalibration was performed daily during testing to maintain accuracy.

Table 2. Calibration and Validation Results of the Instrument

Calibration Method	Average Deviation (pH)	Accuracy (%)	Correlation with Standard Instrument (R^2)
Two-point calibration (pH 4, 7)	±0.07	97.30	0.985
Three-point calibration (pH 4, 7, 10)	±0.04	98.80	0.993

The calibration results showed that the instrument readings approached the buffer reference values, with an average deviation of ±0.07 pH for two-point calibration and ±0.04 pH for three-point calibration. Validation was performed by comparing the instrument's measurement results with those of a standard laboratory pH meter. This yielded a strong linear correlation with $R^2 > 0.98$ across all pH ranges (2.8–10.2). These results demonstrate the instrument's reliability (Hong et al., 2021; Ismaini et al., 2023; Nair et al., 2025; Sugiharto et al., 2023).

Product Design and 3D Printing: Casing Evaluation

The casing design, which was printed using an FDM 3D printer, demonstrated optimal ergonomics and good structural strength. The PLA material provides sufficient rigidity to protect sensors and electronic boards while maintaining a lightweight and cost-effective structure. Moreover, the casing can be reprinted in less than two hours at a low cost, ensuring practicality and reproducibility for prototype development (Bajre et al., 2025; Botero-Valencia et al., 2022; McCole et al., 2023).

Figure 1. Prototype of a digital pH and temperature measuring device with a 3D-printed casing design

The modular casing design can be digitally modified using CAD software to meet specific requirements, such as field testing or integration with external power modules. The fabrication process utilizes Ultimaker Cura's slicing feature, enabling precise control of infill density, layer height, and printing speed. This demonstrates that 3D printing–based product designs can effectively support the rapid and efficient development of industrial and laboratory instruments (Bajre et al., 2025; Briciu-Burghina et al., 2022; McCole et al., 2023; Aulia et al., 2024).

Conclusion

A prototype of a pH and temperature meter based on an Arduino Uno with automatic temperature compensation (ATC) was successfully designed, constructed, and validated using fifteen consumer products across different categories. The results indicated high accuracy (±0.1 pH), stability, and responsiveness within the temperature range of 30–40 °C. The implementation of three-point calibration yielded more reliable measurements compared to the two-point method, while the PLA-based 3D-printed casing provided adequate mechanical protection and cost efficiency. Despite these positive outcomes, this study was limited by the relatively narrow temperature range and the restricted number of tested product categories. Future research should extend testing to a wider temperature spectrum, include long-term stability analysis, and explore the integration of wireless data transmission or IoT-based monitoring. Scientifically, this work demonstrates the potential of combining low-cost microcontrollers and additive manufacturing for the development of precise, modular, and accessible analytical instruments applicable in education, laboratory environments, and small-scale industries.

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Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

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