

Design and Evaluation of a Wearable System Using Paper-Based pH Colorimetry and Skin Conductance for Skincare Monitoring

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Abstract

The skin barrier protects from moisture loss and maintains optimal physiological activity between the skin and its environment, therefore providing a pH-balanced electrochemical environment; it also protects skin against stressors (i.e., environment) and pathogenic organisms (bacteria, viruses, etc.) when functioning properly. In contrast, compromised skin will result in dry skin, acne, eczema, and premature aging. The majority of traditional approaches to skincare are subjective and focused on what may be noticed at that moment. Self-reported information and visual inspection do not address the actual condition of the skin or underlying problems. Even though there are some limited clinical tests available (e.g., corneometry, skin pH probe), the unacceptable size, price, and/or impracticalities associated with prolonged daily use render those tests ineffective in this regard. Because of these apparent needs, an innovative solution is required; therefore, a skin health monitoring system was developed. This band combines a Galvanic Skin Response (GSR) sensor using colorimetric and electronic methods, along with a colorimetric pH sensing, to create a convenient, non-invasive method for monitoring skin barrier health. The band attaches a color-changing paper strip that gives information about the skin's acidity to a small optical readout module. The GSR sensor will also provide information on skin hydration and stress levels by measuring the electrical resistance of the skin. Results from both sensors will be sent to an app on your smartphone that will give you graphs and trends based on the results of these sensors and give you personalized recommendations based on the results. Early results from the prototypes of this project indicate that creating a low-cost, disposable smart pH sensor and GSR monitor and putting them into a compact wearable device is possible.

Keywords: Skin Health, pH scale, GSR Sensor, Haptic feedback, Cosmetic Recommendation, Early skin disease prevention

1 Introduction

Human skin acts as a barrier for staying hydrated, balancing pH levels, and preventing invasion from harmful microbes. When that barrier has been compromised, it causes dermatological issues such as dry skin, eczema, and premature aging. A significant amount of adults globally experience sensitive skin, while atopic dermatitis is also a common skin condition faced by children and adults. In addition, an estimated 300 billion dollar plus market for cosmetics exists in 2024, which reflects people’s increased desire for custom-made and preventive solutions for skincare [13]. As a result, the decision is mainly based on preventive interventions on what someone physically sees, or what someone perceives via subjective reporting from others; hence, any interventions undertaken must be effective. Currently, there are only objective assessment tools available. For example, corneometers may determine hydration levels of the skin, and pH probes may find acidic substances on the skin. The corneometer must only be used in a clinic or laboratory. These devices are expensive, bulky, and do not allow for continuous usage. Some alternatives exist for these, such as mobile phone camera skin assessments or portable hydration gauge measurements; however, both have challenges due to differences in devices, limited accuracy, and they cannot be assessed consistently over time. Popular devices exist, e.g., smartwatches or fitness trackers; however, none of them support direct monitoring of skin barrier health. By combining a paper-based colorimetric pH sensor (which can be discarded after use) with GSR electrodes, researchers have created a wearable smart band that can collect data about moisture levels and reactions to stress through easy-to-use and inexpensive means. This gives the wearer a way to monitor their skin barrier health using laboratory-quality sensors in combination with everyday usage. As such, the proposed method called the Dermaband provides an affordable, effective means of evaluating the person’s skin barrier to prevent further damage or irritation.

2 Literature Review

M. Akdeniz et al. [1] in their study explored the role of TEWL as a key indicator of skin barrier integrity, framing it as a quantifiable measure of water escaping through the epidermis. The authors compared open-chamber, closed-chamber, and condenser devices, noting their varying sensitivities to environment and movement. They emphasized the importance of controlled conditions, acclimation, and probe handling for reproducible readings. However, limitations remain, including high sensitivity to drafts, sweat, and

probe pressure. This work highlights TEWL as a gold standard tool but underscores the need for standardization in wearable applications.

The EEMCO guideline by Piérard et al. [2] created a framework for standardised measurements of TEWL, detailing the environmental requirements, use of probes, and participant preparation. The importance of acclimating subjects, as well as avoiding washing or lotion application before measurements and using multiple measures averaged out to reduce the effect of noise (variation within the same repetition), was emphasised as a critical component of the protocol developed in this work. Although the protocol developed by the EEMCO group provided a solid foundation for TEWL measurement, the primary focus was on static and laboratory-based methods of TEWL assessment. Therefore, the framework is a basis for establishing a consistent and reproducible standard by which all studies on TEWL can be compared.

The WASP project by Sivakumar et al. [3] has developed a wearable Trans Epidermal Water loss (TEWL) measurement device that has two humidity sensors and a smart filtering capability that allows for continuous, real-time measurement of TEWL while participating in normal daily activities. This wearable device’s accuracy was validated by comparison with commercial products. There are still challenges in terms of stabilization time and chamber design, but this work represents an important advance in developing wearable TEWL measurement devices for the future. However, the device’s cost and complexity of fabrication will likely limit widespread use at this time.

The reliability and variations with different TEWL devices have been analyzed by Klotz et al. [4]. They found differences between the open, closed, and condenser chamber methods due to the influence of air flow, sweat, and skin site. Although benchmarking data presented in this study may be valuable, they lacked agreed-upon universal calibration standards and thus would not allow direct comparison between results from various devices or laboratories.

The work of Stefaniak et al. [5] was to create standards for skin pH determinations. They found that there were significant influences by environment and manipulation of the electrode (e.g., cleaning, etc.). The importance of stable temperatures and replicating readings when measuring the pH value on skin was highlighted. Additionally, they concluded that the opportunity for continuous or wearable monitoring of skin pH will require modifications to the current methodology. However, it is still regarded as the gold standard for skin pH research.

In [6], Joachim W. Fluhr et al. presented a multi-sensor TEWL system incorporating different humidity and temperature measurements from which a more stable and reproducible measurement could be created from those varying devices. In addition, it maintained consistency over time with respect to the output reported compared to single-sensor devices. The authors also found that even with the added environmental factors of humidity/temperature, this system experienced challenges in non-ideal environmen-

tal conditions. Overall, this paper provides justification for implementing a multi-point sensing approach into wearable devices capable of TEWL measurements.

A review by Manjakkal et al. [7] focused on how flexible pH sensor designs (which include IrOx electrodes, polyanilines (PANI) polymers, and ion-sensitive field effect transistors (ISFETs)) addressed several issues with previous generation pH sensors. The review discussed the issues of sensor drift, hysteresis, and sensor encapsulation, and some suggested strategies for calibration and low-power readout of flexible pH sensors. Although technology has improved dramatically, many of the flexible pH sensor designs still exist only as prototypes in the laboratory and have limited commercial use. This review is a valuable resource for selecting pH electrode materials for use in wearable devices.

Du Plessis Johan and others [8] provide a practical study that distinguishes between TEWL (trans-epidermal water loss or water leaving the skin) and hydration (the level of water that exists in the stratum corneum) and how moisturizers affect both of these levels differently. They also emphasized the importance of environmental confounding variables (such as sweating and occlusion) and proposed measurement protocols to differentiate true changes from background noise; however, the project continued to focus on the use of traditional measurement devices rather than any wearables, thus supporting the need to evaluate both TEWL and hydration in conjunction.

The present review by Mao et al. [9] presents the latest developments in skin-wearable technologies utilised in the non-invasive monitoring of health. The current review provides a comprehensive summary of electrical, electrochemical, and photoelectrical methods for sensing using flexible electronics. Material selection and fabrication and integration strategies for optimal comfort, precision, and durability have been highlighted by the authors. Moreover, there is increasing interest in the use of ultrathin stretchy substrates that conform to the skin for real-time monitoring. There is also growing interest in new uses of shadows and hydration analysis, as well as multimodal biosensing.

The present paper by Song et al. [10] presents an overview of flexible biosensors that continuously monitor physiological and biochemical signals in real time. Specifically, it discusses wearable devices for detecting hydration, temperature, urine analysis, and stress levels. This paper discusses the most recent technological advances in stretchable electronics, printed electrodes, and hybrid materials that allow these devices to function properly when bent or moved. In particular, skin interface-based biosensors are described extensively; these types of biosensors are able to provide constant tracking of long-term illnesses, enabling physicians to diagnose diseases much earlier.

This review by Manjakkal et al. [11] examined the available data on using flexible potentiometric pH sensors for sweat and skin analysis in wearable devices. It included an overview of the different electrode materials including iridium oxide (IrO_2), polyaniline, and various metal oxides used as electrodes, detailing their sensitivity characteristics, drift properties, and fabrication requirements. It highlighted several of the practical challenges

associated with flexible pH sensors such as biocompatibility, need for encapsulation, the difficulty of maintaining long-term calibration stability, and interfacing them with low-power electronics. Additionally, the authors discussed the opportunities that pH sensors offer for the personalization of healthcare, fitness monitoring, and the early identification of skin disorders.

The article by Soh et al. [12] describes the development of an AI-based method for estimating the hydration of the skin and transepidermal water loss (TEWL) using smartphone photographs of the skin (face or other). The estimated level of hydration is based on color, texture and reflectance features extracted from these images. The development eliminates the traditional need for physical measurement devices, providing a low-cost and scalable alternative for diagnosing skin conditions. The performance of this method has been shown to produce comparable levels of accuracy with H₂O meters, suggesting that there is a high potential for application in the field of digital dermatology.

Most techniques used to measure TEWL and skin pH as indicators of skin barrier health use laboratory instruments that are expensive, large, and impractical for use in non-laboratory settings (e.g., on the body while doing normal day-to-day activities). Recently developed wearable and flexible sensing approaches show promise, but are limited by their complexity, high costs, sensitivity to the environment and lack of general acceptance. Therefore, there is an unmet need for a low-cost, simple-to-use wearable system that integrates objective skin hydration, stress, and pH measurements and provides real-time analysis and individualized feedback for monitoring the condition of the skin on a daily basis.

3 Methodology

Implementation Strategy: The proposed wearable skin health monitoring system integrates two complementary sensing modalities: a paper-based colorimetric pH sensing and a GSR sensor. The methodology involves the design, fabrication, integration, and testing of these components within a compact wearable band, along with the development of a companion mobile application for data interpretation. The development of the wearable smart band involves a multi-layered methodology integrating hardware, sensing, data acquisition, processing, and application-level decision-making. The steps are outlined as follows:

Step 1 - Sensor Selection & Calibration: A disposable pH paper strip embedded with pH-sensitive dye was used to fit within the wearable band. The strip changes color in response to skin acidity variations (pH 4–7). A color sensor consisting of an LED light source and photodiode-based detector was employed to capture and digitize the colorimetric response.

Step 2 - GSR Sensor Integration: Two conductive electrodes were embedded

on the inner strap of the band to measure skin conductance. The variation in electrical resistance correlates with skin hydration levels and sweat gland activity. Analog signals were conditioned and processed using a low-power microcontroller (ESP32).

Step 3 - System Integration and Data Processing: The microcontroller was used to acquire inputs from both sensors and then transmit the processed data wirelessly via WiFi to a smartphone application. The mobile app was designed to visualize pH and hydration trends, generate alerts in case of barrier disruption, and provide personalized skincare insights.

Step 4 - Evaluation and Validation: Prototype was tested for sensor validation and verification of received data under varying skin conditions. Preliminary results confirmed the feasibility of combining disposable pH sensing with continuous GSR monitoring for real-time, non-invasive assessment of skin barrier health.

3.1 Testing Procedure

The testing procedure for the given implementation strategy is as shown in Fig. 1. The complete workflow includes skin acidity testing along with the user's hydration and stress levels detection. All this data is further analysed for skin health behaviour and the early detection of possible skin diseases.

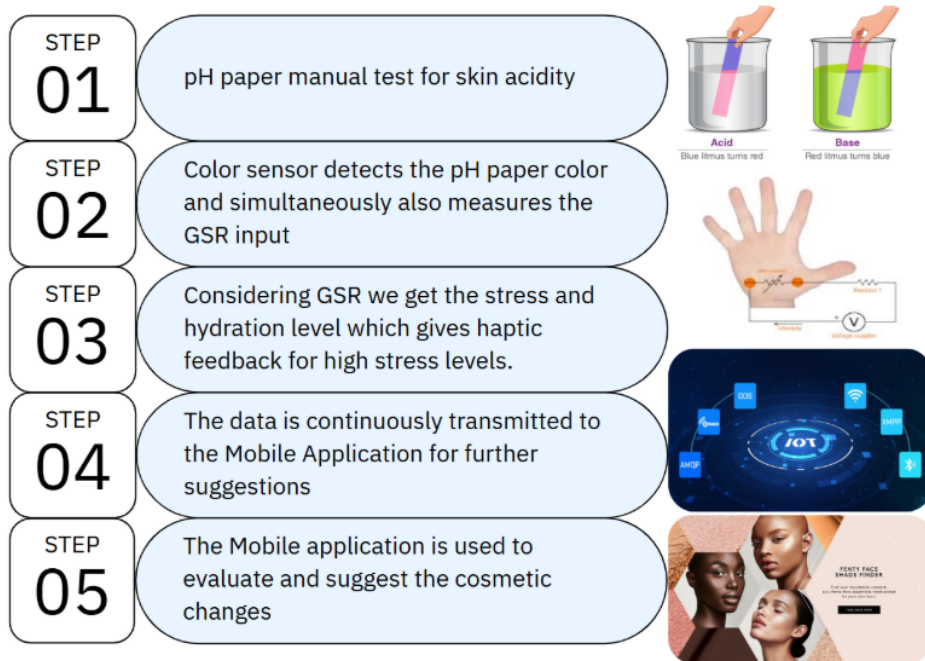


Figure 1: Testing procedure for the proposed implementation

Step 1 – pH Paper Manual Testing: The first stage includes assessment of the acidity of the skin surface using disposable pH paper strips. The user's wrist/face region is cleaned and left untouched for 30 minutes before testing to ensure accurate readings.

The pH strip is gently dabbed onto the skin for a few seconds to absorb surface moisture, and the pH paper strip's color is used as an indication of the skin acidity.

Step 2 – Optical Color Readout and GSR Data Collection: The pH paper, once dabbed on the skin, is placed beneath the digital color sensor TCS34725 embedded in the wristband. The sensor detects R: Red, G: Green, B: Blue and C: Clear values of the strip, which is later converted to the corresponding pH levels. Also, a Galvanic Skin Response (GSR) sensor is used to measure electrical conductance between the skin electrodes. These values reflect hydration status and stress related changes in skin moisture. Both sensors are connected to the ESP32-S3 Mini microcontroller, which collects and processes the incoming data signal in real time.

Step 3 – Signal Processing and Interpretation: Raw sensor output signals are processed by the ESP32 microcontroller. For the color sensor, the RGB readings are mapped to pH values through calibration against known buffer solutions. The processed value is shown in the application as the skin acidity percentage as compared to the pH scale. GSR sensor raw values are calibrated for representing hydration and stress respectively. The processed data is converted into percentage for the hydration and low, moderate or high levels for the stress. The complete system is as shown in Fig. 2.

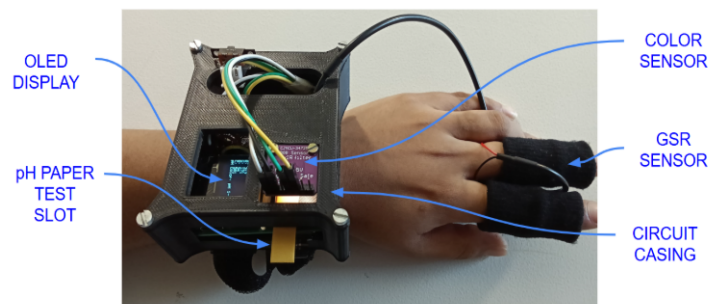


Figure 2: Prototype Front View

Step 4 – Data Transmission and App Integration: The ESP32-S3 Mini transmits the raw values wirelessly by connecting the microcontroller to the available WiFi. The data is sent to a smartphone application which was developed using React Native App. The app receives real-time skin conditions using which it analyses the skin health and displays the hydration stress and skin acidity levels. The user interface also takes personal information input from the users such as age, gender, Fitzpatrick skin type, and known cosmetic allergies to enable personalized interpretation.

Step 5 – Recommendation and Feedback System: Based on the incoming data, the mobile app provides skincare suggestions and preventive recommendations. For instance, if the sensors detect low hydration levels, it may suggest products with contents like hyaluronic acid. When high stress or abnormal readings are observed, the device provides a haptic alert via a vibration motor to prompt immediate attention as shown in Fig. 3.

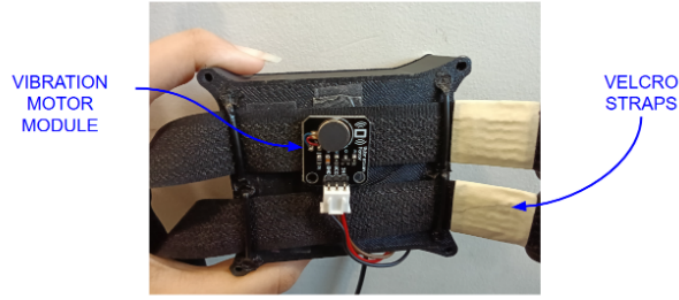


Figure 3: Prototype Back View

Step 6 - Skin Health Trend Analysis: Over time, trend data enables early detection of potential skin barrier dysfunctions. It helps analyze the possible skin disease which can take place over a period of time due to prolonged dehydration or high skin acidity. Hence, helping in early detection of the possible skin health risks and alert to focus on skin health.

3.2 Skin Health Monitoring Application

The DermaBand application has multiple screens in order to perform the given operations. These screens are as described further.

Screen 1: Splash Screen

It is a welcome screen for the application. It includes the app logo and an animated entrance. This screen uses `Animated.timing()` and `Animated.spring()` for fade-in and scale effects. After this screen it gets auto-navigated to the Login screen after 2 seconds using `setTimeout()`. This screen can be seen in Fig. 4(a).

Screen 2: Login Screen

The Login Screen enables secure user authentication by allowing users to enter their email address and password credentials. Input validation is performed in real time, with email formats verified using a regular expression as `/^[^\s@]+@[^\s@]+\.[^\s@]+$/` to ensure correctness before authentication proceeds. Upon successful login, the authenticated user's session data is stored locally using persistent storage to maintain login state. This screen further navigates to the Profile setup page. It is shown in Fig. 4(b).

Screen 3: Profile Setup Screen

The profile setup screen is built to collect the data of the user for more personalized results. The considered parameters were name, age, gender, skin type using Fitzpatrick scale and the various sensitivities like fragrance, preservatives, alcohol, chemical sunscreens and soap/alkalines. This screen uses controlled components with `useState()` for form inputs. It saves profile data to `AsyncStorage` as JSON. This screen helps to validate the required fields before navigating to the SkinAnalysis screen. The profile setup screen is as seen in Fig. 4(c).

Screen 4: Skin Analysis Screen

This screen acts as the core screen of the application. It shows the real-time GSR and the skin pH levels. These raw values are converted into hydration level, stress level and the skin acidity level. This screen converts raw GSR ADC value to voltage $\rightarrow$ microsiemens conductance using the formula: $\mu S = (\text{voltage}/0.132)$ where voltage = $(\text{ADC}/4095) \times 3.3\text{V}$. Hydration % = $\{(\text{GSR} - \text{GSR}_{\min})/(\text{GSR}_{\max} - \text{GSR}_{\min})\} \times 100$ where $\text{GSR}_{\min} = 3.5 \mu S$ and $\text{GSR}_{\max} = 10 \mu S$ for obtaining the hydration percentage. For stress it maps GSR conductance to stress levels ($< 2 \mu S$ = relaxed, $> 30 \mu S$ = extreme stress). The pH values are determined by parsing the RGBC (Red, Green, Blue, Clear) values from the TCS34725 color sensor. The sensor reads the color-changed pH paper strip, and the hexadecimal RGBC values are converted to decimal format. Color dominance ratios are calculated from these values, which are then mapped to corresponding pH values in the range of 3.0–9.0 through a calibration process using known buffer solutions. This screen fetches the data from ESP32 endpoint every 2 seconds using `setInterval()`. This screen is as visualized in Fig. 4(d).

Screen 5: Personalized Care Screen

This screen is used to provide the user suggestions and the recommendations for their skin health as per the values received in the previous screen. In the same screen the skin disease risk prediction is performed and displayed. Product Recommendations is done through a rule-based engine and if hydration levels are detected to be $< 20\%$ then intensive serums are recommended similarly if pH value is > 6.5 then various acidic toners are recommended. Also if stress levels are $> 20 \mu S$ then the calming ingredients are suggested. Now for the skin health trends risk assessment is done using calculations like threshold logic – low hydration + high pH = acne/dermatitis risk; dehydration $< 15\%$ = xerosis/eczema risk; high stress = cortisol-induced breakouts. This screen is shown in Fig. 4(e).

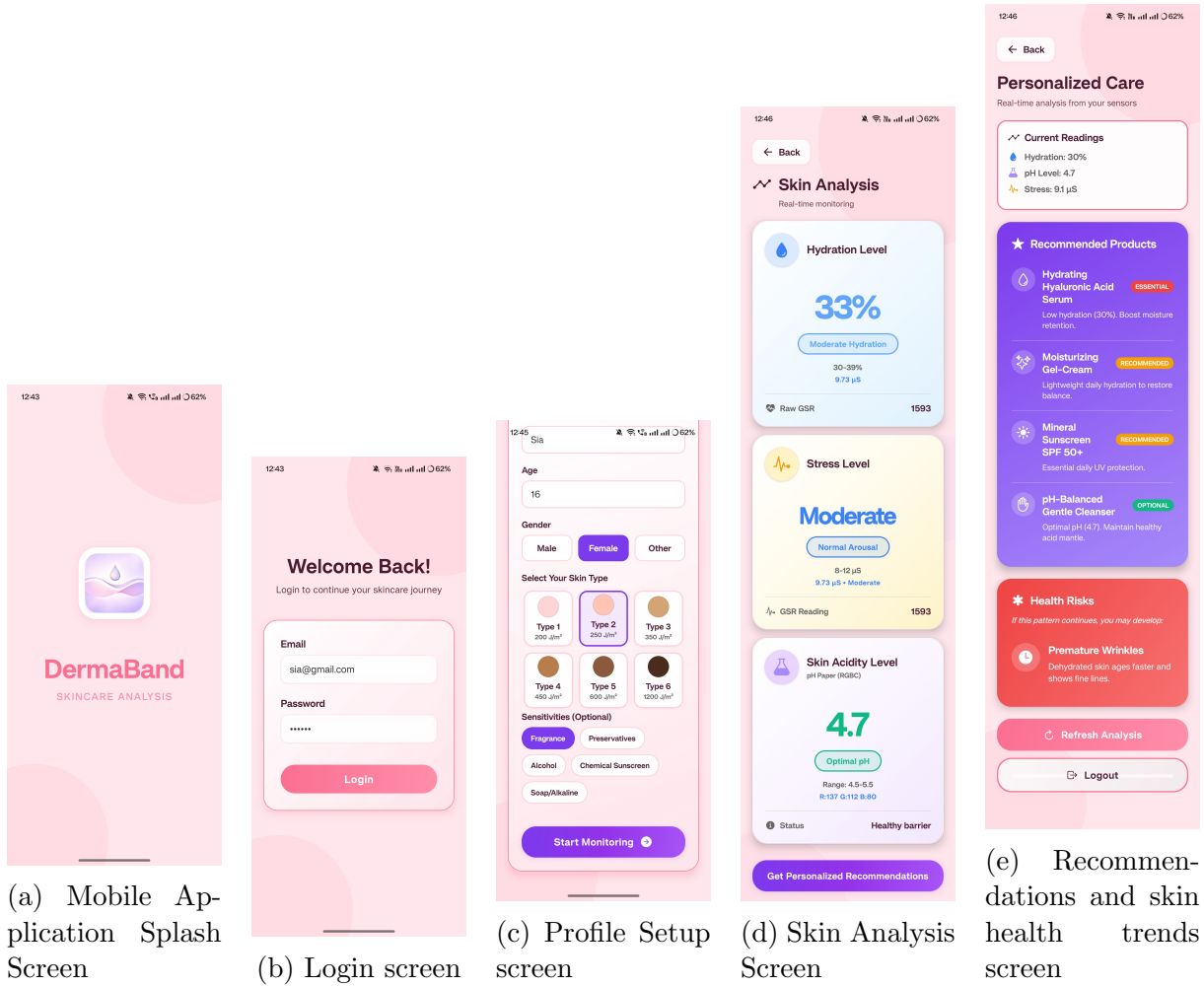


Figure 4: Mobile Application Screens

4 Results & Discussion

4.1 pH Measurement Results

The colorimetric pH sensing technique successfully obtained skin surface acidity using disposable pH paper and an embedded color sensor. pH value depicting the skin acidity value for a number of users is as shown in Table 1.

Table 1: Skin Acidity values of few users

Users	Skin pH
U1	5.1
U2	5.4
U3	5.8
U4	6.2
U5	4.9

4.1.1 pH Sensor Accuracy and Error Analysis

Multiple users were tested on pH detection capabilities of the system with voltage readings ranging from 4.9 – 6.2, being in the usual skin pH range (4.0 – 7.0). This information shows that the system can differentiate between users based on their skin surface acidity, demonstrating functional detection of pH levels. The system was tested on five users (U1–U5), successfully detecting variations in skin pH ranging from 4.9 to 6.2. These values are consistent with established dermatological literature indicating normal skin pH ranges from 4.0 to 7.0 [5]. Further validation against clinical-grade pH measurement devices is needed to establish absolute accuracy.

4.2 GSR-Based Hydration and Stress Analysis

The GSR sensor demonstrated accurate sensitivity to changes in skin conductance related to the hydration and stress levels. Participants with visibly dry skin displayed consistently lower baseline conductance values compared to hydrated skin conditions. Additionally, stress-inducing stimuli resulted in rapid phasic peaks in GSR signals, validating its dual role in hydration and stress assessment. The GSR outputs for different skin types are shown in Table 2. Whereas Table 3 shows the stress response of the different conditions.

Table 2: GSR Values for different skin types

Skin Condition	Mean GSR (μS)	Hydration Percentage (%)
Well-hydrated	9.2	~90%
Normal	6.8	~55%
Dry	4.1	~10%

Table 3: GSR values for stress detection

Condition	Average GSR Peak (μS)	Indications
Resting	0 – 4	Low
Mild Stress	4 – 10	Moderate
High Stress	10 and higher	High

4.3 Personalized Skincare Recommendation Outcomes along with Skin Health Trends

Based on the hydration, stress, and skin acidity levels, the application gives personalized recommendations on the content of the cosmetic in order to help improve the skin health and maintain a good skin barrier to avoid the deterioration of the skin health over time. Table 4 shows the possible recommendations for different readings from sensors. Along

with recommendations, the application also gives skin health trends to give an early detection of skin health and prevention. Table 5 displays the various trends of skin health.

Table 4: Personalised Skincare Recommendations for few users

User	pH	GSR (μ S)	Detected Issue	Suggested Action
U1	5	4.2	Low hydration	Hyaluronic acid serum
U2	6.3	4.5	Alkaline + mild dryness	Barrier repair cream
U3	5.5	8.9	Normal	Maintain routine
U4	6.5	3.9	Mild stress + Alkaline	Stress relief + hydration
U5	5.1	6.7	Stress + Mild dryness	Moisturizer

Table 5: Skin Health Trends

Current Skin Condition	Possible Risk Over 10 Years	Possible Risk Over 20 Years
Normal hydration & normal pH	No significant increase	Baseline population risk [5, 8]
Mild dryness (low GSR)	Early barrier weakening	Slight $\uparrow$ photoaging risk (5–8%) [1, 8]
Chronic dryness (persistently low GSR)	Barrier damage, inflammation	$\uparrow$ Non-Melanoma Skin Cancer [NMSC] risk by $\sim$ 20–25% [1]
Elevated skin pH (>6.5)	Chronic inflammation	$\uparrow$ precancerous lesions ($\sim$ 15–20%) [5, 7]
Dry skin + high stress (GSR spikes)	Accelerated aging	$\uparrow$ UV damage susceptibility ($\sim$ 25–30%) [9, 10]
Frequent cosmetic irritation	Pigmentation disorders	$\uparrow$ chronic inflammation ($\sim$ 15–20%) [2, 8]
Barrier dysfunction (dry + alkaline)	Actinic damage	$\uparrow$ NMSC risk ($\sim$ 30–40%) [1]

5 Limitations

There are some limitations with the current system. The pH paper strips are single-use and need to be replaced after every measurement, which creates ongoing costs and requires intervention by the user. Also, the system is dependent on having an available WiFi network to transmit data to the mobile app, so users will not be able to use it in areas where there are no networks available. In addition, the current prototype is currently designed as a wristband form factor and may not be appropriate for measuring the pH of the skin on the face, as referenced in the instructions for the testing procedures. GSR sensor calibration thresholds ($GSR_{min} = 3.5 \mu S$ and $GSR_{max} = 10 \mu S$) are fixed and do not take into account physiological variations between individuals in a diverse population.

Furthermore, environmental factors such as temperature and humidity may impact the stability of the pH paper colour and GSR readings, but this was not specifically quantified as part of this study. Another area needing further research is long term wearability of the sensor, drift of the sensor over time and battery life under constant monitoring. Currently, the system has only been tested with a small number of participants (5), therefore additional research is required on a larger sample in order to establish if the results with this system can be generalized across different skin types, ages and conditions.

6 Data Privacy, Security, and Ethical Considerations

Data stored in this application can include: personal health data (skin pH, hydration levels, and stress) and user profile information (age, gender, Fitzpatrick skin type, and cosmetic sensitivities). The data will be sent wirelessly from the ESP32-S3 microcontroller to the React Native mobile app through the use of WiFi. Currently, the mobile app saves the user profile data to a local device via AsyncStorage in a JSON format. However, the paper does not provide any information about data encryption protocols, security features for user authentication, compliance of the current design with health data protection regulations (such as GDPR and HIPAA), or future development efforts to ensure end-to-end encryption of data moving to/from the mobile app as well as secure storage of data on a local device and procedures for obtaining informed consent from participants and ethical approval to collect data from human subjects via institutional review boards. In order to meet the needs of users and comply with current data protection requirements, there should be a mechanism in place that provides transparent information to the user regarding the data being collected, the method of data collection, the data being stored in the mobile device’s local storage, how the data will be used, and whether or not data will be deleted. Additionally, users should have access to informed consent procedures prior to participating in any clinical study or providing health-related personal data.

7 Conclusion

Using inexpensive sensors that measure skin hydration and stress to assess the barrier function and display the results of this method via a smartphone mobile app, this research introduces a low-cost, wearable system for real-time assessment of skin barrier health. By utilizing a colourimetric pH paper and optical colour sensor together with an ESP32-S3 microcontroller to capture continuous pH and skin hydration data, we have created an effective solution for automated skin assessment as part of a daily skincare routine. The data collected in experiments has reliably shown the presence of chemical and physical changes in hydration, skin barrier function (dryness), and stress within the physiological range of pH, both before and after using the wearable device. The companion mobile app

is user-specific, as it collects and analyses different variables regarding each individual’s skin condition (age, Fitzpatrick skin type, and history of allergy to cosmetic ingredients). This enables customized recommendations to each individual based on their unique needs. The proposed system represents a model that bridges the current gap between traditional clinical skin assessments and the general population by providing an easily accessible and scalable system for tracking individual daily skincare. The final phase of the research will include future efforts to integrate additional biomarkers into the wearable system (transepidermal water loss and temperature) and implement machine learning algorithms for predictive risk assessment, further minimise the size of the sensors, and expand clinical validation for long-term continuous monitoring on diverse skin populations.

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