International Journal of
INTELLIGENT SYSTEMS AND APPLICATIONS IN ENGINEERING

ISSN:2147-6799 www.ijisae.org Original Research Paper

Design and Modelling of a Glucose Optical Sensor for Diabetes Monitoring

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Submitted: 24/04/2023 **Revised**: 25/06/2023 **Accepted**: 06/07/2023

Abstract: The prevalence of diabetes world- wide necessitates frequent monitoring of blood glucose levels for appropriate insulin dosing and risk management. Current techniques involve invasive finger pricking with lancing devices, which can be painful and may result in infections. This study proposes a non-invasive approach using near-infrared (NIR) LED light to illuminate a glucose solution that mimics blood and the transmitted photons are further processed to obtain glucose levels. The impact of glucose concentration on NIR sensor output voltage was examined across varying concentrations, and a glucose sensor circuit was simulated using LTspice software to test efficacy across a range of concentrations. The proposed study demonstrated the feasibility of using NIR LED light and the associated sensor circuit to monitor glucose concentrations non-invasively. The findings indicated that higher glucose concentrations resulted in lower sensor output voltages. The regression analysis allowed for the development of a mathematical model to estimate glucose concentration based on the observed output voltage. This research offers a promising approach for the development of non-invasive glucose monitoring systems, which could greatly benefit individuals with diabetes by eliminating the need for frequent finger pricking and associated complications.

Keywords**:** *Blood glucose measurement, Diabetes monitoring, NIR sensor, Non-invasive.*

1. Introduction

Diabetes mellitus is one of the most widespread chronic disorders affecting people worldwide [1]. It is a type of metabolic disease in which the body's level of blood glucose (blood sugar) drastically rises above normal levels. Symptoms of this ailment include failure of glucose metabolism and hyperglycemia. Inherited factors, immunological issues, and poor lifestyle choices account for the vast majority of cases of this illness in humans. Increased blood sugar levels can be caused by inappropriate insulin response in body cells, insufficient insulin production in blood cells, or any combination of these two factors [2]. In the human body, diabetes can cause severe problems like heart failure, kidney failure, eye impairments, and many more [3]. Hence, monitoring blood glucose levels in the human body is critical.

The World Health Organization (WHO) estimates that by 2045 there will be 700 million people with diabetes worldwide, and in the United States, the numbers will rise to 39.7 million by 2030 and 60.6 million by 2060 [4]. In addition to the vast majority of people who have already been diagnosed, a large portion of the population has not been identified for various reasons or is at high risk. As a result, the diagnosis and treatment of diabetes have gained great practical relevance and economic advantages. Hence, the prevention of diabetes has received increased attention in many nations, especially developed countries.

Blood sugar monitoring techniques can be broadly classified into two categories, namely, invasive and non-invasive procedures. The invasive methods cause injuries to human skin, while the latter is devoid of such incidents. Invasive blood glucose level measuring technology is mainstream, practical, and convenient nowadays, resulting in hospitals and home glucometers using the same method. Monitoring blood glucose levels requires collecting and analysing blood samples in vitro. Blood samples from patients are collected in hospitals, and an automated biochemical analyzer is used to get an accurate reading of the amount of glucose in their blood. Despite its accuracy, the method is unfit for continuous monitoring of the glucose level in diabetic patients since it necessitates a lengthy, laborious operation and a large volume of venous blood extraction. An invasive electronic glucometer is often the instrument of choice for self-monitoring blood glucose levels at a specific time. Invasive blood glucose monitors typically employ glucose oxidase biosensors, which collect blood from the fingertip using a disposable paper strip and then determine blood glucose concentration using the chemical reaction current in the strip [5, 6].

Non-invasive blood glucose monitoring techniques measure blood glucose levels in humans without creating any tissue harm. They are broadly categorized into optical,

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microwave, and electrochemical techniques. Near-infrared reflectance spectroscopy (NIRS), polarized optical rotation (POR), Raman spectroscopy, and optical coherence tomography (OCT) are examples of optical technologies. NIRS is a technique that uses light to measure glucose levels. It works by shining light on the skin and measuring the amount of light that is reflected or transmitted. The amount of light is then used to calculate the glucose level. The NIR spectroscopy allows signals to penetrate tissue around 1 and 100 millimetres deep for the purpose of monitoring glucose levels [7, 8]. The intensity of the light at specific NIR wavelengths is affected by the glucose concentration in the skin tissue.

Optical Coherence Tomography (OCT) [9, 10] is a technique that uses light waves to create a 3D image of the tissue. It can be used to measure glucose levels by analyzing the changes in the tissue caused by changes in glucose concentration. Raman spectroscopy [11, 12] uses laser light to measure glucose levels. The laser interacts with the glucose molecules, causing them to vibrate in a unique way that can be measured and used to calculate glucose levels.

Polarimetry is a technique that measures the rotation of polarized light by optically active substances, such as glucose [13, 14]. Polarized optical rotation can be used for glucose measurement by analyzing the rotation of plane-polarized light as it passes through a glucose-containing solution or tissue. In polarimetry, a polarizer is used to produce a beam of plane-polarized light, which is then passed through the sample containing glucose. As the polarized light passes through the sample, it is rotated due to the presence of optically active molecules such as glucose. The amount of rotation is proportional to the concentration of glucose in the sample. The degree of rotation of the plane-polarized light can be measured using a polarimeter, which consists of an analyzer that measures the angle of rotation of the polarized light as it exits the sample. By comparing the measured rotation angle with a calibration curve, the concentration of glucose in the sample can be determined. Polarimetry has been used for glucose measurement in laboratory settings, but it is not widely used for non-invasive glucose monitoring due to the limited penetration depth of polarized light in biological tissues.

Microwave-based techniques have been investigated for non-invasive blood glucose measurement, although they are not currently in widespread use [15, 16, 17]. The basic principle behind microwave-based glucose sensing is that glucose molecules exhibit dielectric properties, which can be measured using microwaves. In microwave-based glucose sensing, a low-power microwave signal is transmitted into the tissue, and the signal that is reflected back is analyzed to determine the glucose concentration. The dielectric properties of glucose cause the microwave signal to be attenuated and phase-shifted, and these changes can be measured and used to calculate the glucose concentration. While microwave-based glucose sensing holds promise for non-invasive glucose monitoring, more research is needed to develop and validate the technology. Challenges include the need for accurate positioning of the sensing element, the potential for interference from other substances in the tissue, and the need for calibration and validation against reference glucose measurements.

This paper outlines the design and experimental study of a non-invasive blood glucose sensor that employs LED light sources and a photodiode array capable of detecting the specific wavelengths as the sensing device. The sensor is tested in a low light environment with varying concentrations of glucose solutions containing blood-mimicking components. The experimental results show very good correlation with actual glucose levels as measured using a commercial blood glucometer. The paper is organized into five sections; Section 2 describes the principle of NIR-based blood glucose measurement, Section 3 outlines the sensor design, Section 4 discusses the results and its analysis, and finally Section 5 concludes the paper.

2. Principle Of NIR-Based Blood Glucose Measurement

The fundamental concept underlying the design of the noninvasive NIR-based blood glucometer is the Beer-Lambert law, also referred to as Beer's law. This law is an empirical relationship that correlates the absorption of light to the characteristics of the medium that the light is passing through. According to the law, the amount of light absorbed by a material is directly proportional to the concentration of the material and the distance the light travels through the material. The Beer-Lambert law is commonly used in spectroscopy and other optical measurements to determine the concentration of a substance in a sample, and it can be expressed mathematically as:

$$A = \epsilon l c \tag{1}$$

where A is the absorbance of the sample, ϵ is the molar absorptivity, l is the path length of the sample, and c is the concentration of the sample. Transmittance and reflectance are the two primary methods used to measure light in biological tissues. Transmittance measures the light that passes through a tissue and emerges on the other side, while reflectance measures the light that is scattered back from the surface of a tissue. Transmittance is commonly used in spectroscopy and imaging techniques like optical coherence tomography (OCT), and provides information about the absorption and scattering properties of tissues. Reflectance, on the other hand, is commonly used in imaging techniques such as diffuse reflectance spectroscopy and reflectance confocal microscopy, and provides information about the structure and composition of tissues. The choice of method depends on the specific application and the properties of the tissue being measured. Transmittance may be more suitable for thinner tissues with lower scattering properties [18,19], while reflectance may be more suitable for thicker tissues with higher scattering properties [20, 21]. Fig.1 describes how glucose molecules affect the path of light in a sample tissue.

Near-infrared (NIR) sensors are commonly used in non-invasive glucose monitoring techniques due to their high penetration capacity. NIR sensors can be used on various body parts, including the fingers, arm, forearm, earlobe, and palm. The NIR LED's light can penetrate the deepest section of the veins, where the finest data for measuring blood glucose is acquired. Glucose levels affect the scattering and absorption of light in tissues. When there is less glucose, there is greater scattering, a longer optical path, and thus less absorption of light. Conversely, when there is more glucose, there is less scattering, a shorter optical path, and more absorption of light. Reflected light has a lower intensity in high glucose tissue due to higher absorption than in tissue with lower glucose concentration.

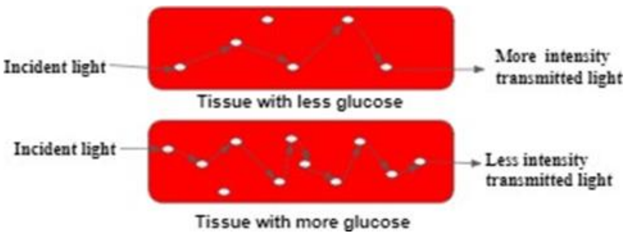

Fig.1. Effect of glucose on the path of light in a sample tissue illuminated using NIR radiation.

3. Sensor Design

The sensor design mainly consists of two stages, selection of optimum wavelength for glucose measurement and circuit design for further signal processing and conditioning. Non-invasive blood glucose measurement is associated with several challenges, which include accuracy, poor glucose specificity and sensitivity, physiological time lag, site of measurement, properties of skin layer and light conditions of sensor environment. In this experimental study, glucose solution is prepared using D-glucose powder and distilled water. To simulate the properties of blood,

blood-mimicking components such as Indian blue ink and titanium dioxide were added to the glucose solution [22,23]. The purpose of using this solution is to create a realistic model for testing the proposed system in a laboratory setting.

3.1. Experimental Setup

The basic setup for fixing optimum wavelength for measuring glucose concentration is shown in Fig.2, which consists of the following components:

- NIR and red/blue LED light sources: These provide the light that is transmitted through the sample containing glucose.
- BPW34 photodiode array: This serves as the photo detector that measure the intensity of the transmitted light. It is sensitive to both visible and NIR light, with a peak sensitivity at 940 nm.
- Optical cuvette: This is a transparent container that holds the sample containing glucose. The cuvette allows the light to pass through the sample and be detected by the photodiode array.
- Multimeter: This is used to measure the output current of the photo-detector, which is proportional to the intensity of the transmitted light.

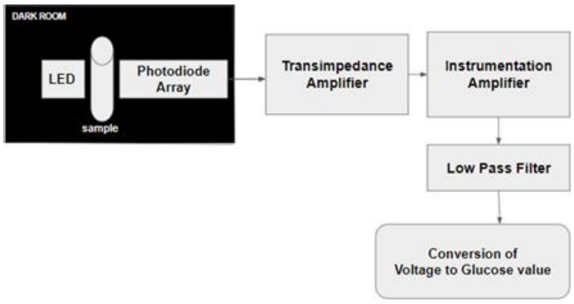

Fig. 2. Schematic of the experimental setup for determining glucose concentration

The optimal wavelengths suitable for measurement of glucose concentration are identified by analyzing the transmitted light intensity in the form of current (mA). The photodetector array measures the amount of light that is absorbed by the glucose-specific enzyme, which is proportional to the concentration of glucose in the sample. The photodetectors measure glucose concentrations at various wavelengths, using different combinations of LED sources. For combination:

a) a blue LED and a 940 nm NIR LED

b) a red LED and a 940 nm NIR LED

The experiments are conducted for glucose concentrations ranging from 10.5 to 266 mg/dl. For all measurements, the temperature in the room was about 36^{O}C without any atmospheric light. The sensor output voltages were measured five times for every glucose concentration. Every parameter was taken with a one-minute delay to achieve a consistent output voltage. Among these two combinations, 940nm and red LED shows significant changes in the output current of the photo detector. Fig.3 represents the overall experimental setup for the proposed non-invasive glucose optical sensor.

3.2. Circuit Design

The second stage of experimental setup involves designing current-to-voltage convertor, amplifier and filtering circuits for further processing of photodetector signal. Fig.4 shows the circuit simulation done using LTspice software.

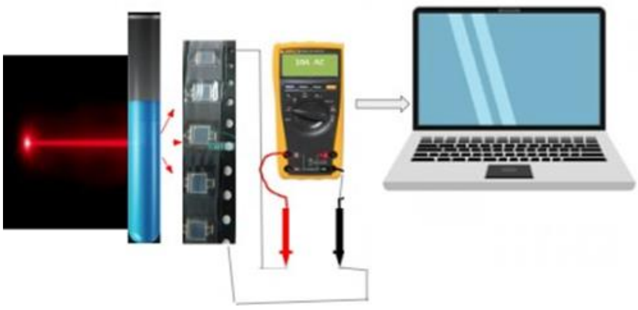

Fig. 3. Experimental setup for determining the optimal wavelength

In the proposed design current to voltage conversion is achieved using a transimpedance amplifier (TIA). The TIA converts the input current to a voltage output, and provides a high level of gain while minimizing noise. The basic structure of a TIA consists of an op-amp (U1) with a feedback resistor (R1) connected from the output to the inverting input. The input current is applied to the non-inverting input of the op-amp. The output voltage of the op-amp is proportional to the input current, multiplied by the value of the feedback resistor. The TIA is commonly used to deal with noise and low gain problems in sensor applications where a small current signal needs to be amplified.

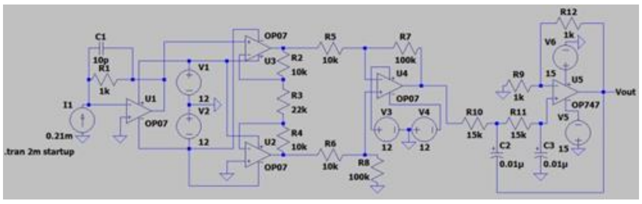

Fig. 4. Sensor circuit diagram

An instrumentation amplifier is used to amplify the voltage obtained from TIA. An instrumentation amplifier is a specialized differential amplifier that is used to amplify small differential signals in the presence of common-mode noise. It is commonly used in measurement and sensor applications where low-level signals need to be amplified accurately and with high precision. The instrumentation amplifier consists of three operational amplifiers (U2, U3 and U4), with two being used as buffer amplifiers (U2 and U3) and the third as a differential amplifier (U4). The input signal is applied to the non-inverting input of the first buffer amplifier, and the inverting input of the second buffer amplifier. The output of the second buffer amplifier is then applied to the inverting input of the differential amplifier, while the output of the first buffer amplifier is applied to the non-inverting input of the differential amplifier. The differential amplifier amplifies the difference between the two input signals, while rejecting any common-mode noise that is present. The gain of the instrumentation amplifier can be adjusted by changing the values of the feedback resistors. The high input impedance of the buffer amplifiers, combined with the high common-mode rejection ratio of the differential amplifier, make the instrumentation amplifier an ideal choice for amplifying small signals in the presence of noise.

The amplified voltage is then filtered using a second-order Butterworth low-pass filter. It uses an operational amplifier (U5) and passive components such as resistors (R10, R11) and capacitors (C2, C3) to implement a second-order Butterworth filter. It is a widely used filter design due to its simple implementation and good frequency response characteristics. The resistor and capacitor values can be chosen to achieve the desired cutoff frequency. The filter has a maximally flat magnitude response, which means that the slope of the magnitude response at the cutoff frequency is zero.

3.3. Correlation of voltage and glucose concentration

Table 1 shows samples of measured photo detector current and filtered output voltage of the sensor circuit (V) with respect to the known glucose concentration. The voltage (V) and the glucose concentration values are plotted on the graph shown in Fig.5.

Table 1: Sample values (Current and voltages) obtained for different glucose concentrations.

Glucose (mg/dl)	Current(mA)	Voltage (V)
10.5	0.4	15
19.6	0.38	14.5
30	0.37	14.15
41.5	0.37	14.15
52.6	0.36	13.8
63.2	0.35	13.38
73.1	0.35	13.38
80.8	0.34	13
95.6	0.34	13
101.8	0.32	12.2
113.9	0.32	12.2
123.5	0.31	11.84
130.9	0.31	11.84
140	0.30	11.5

151.7	0.29	11.1
169.8	0.28	10.75
186	0.27	10.3
202.2	0.27	10.3
213.4	0.25	9.55
226.5	0.24	9.18
238.2	0.23	8.79
245.1	0.22	8.4
257.6	0.22	8.4
266	0.21	8.02

Mathematical modelling using polynomial regression, linear regression analysis, and exponential curve fitting are performed on the experimental data to select a suitable model. Fig.6 shows the comparison of this analysis with known glucose concentration values.

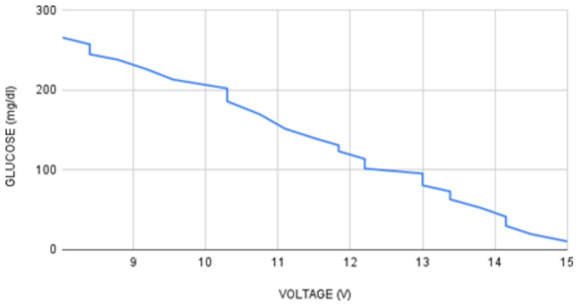

Fig. 5. Plot obtained for known glucose(mg/dl) concentration Vs. voltage(V).

4. Results And Discussion

Non-invasive blood glucose monitoring is a promising approach that could potentially offer continuous real-time blood glucose monitoring without the need for repeated fingertip blood samples. However, there are currently some limitations to this technology that need to be addressed before it can be widely adopted as a replacement for invasive and minimally invasive blood glucose meters. One major limitation is that non-invasive blood glucose monitoring methods are still not as accurate as invasive methods. The current non-invasive methods rely on technologies such as near-infrared spectroscopy, Raman spectroscopy, and fluorescence spectroscopy, but they can be affected by factors such as skin pigmentation, temperature, and hydration levels, which can affect the accuracy of the readings. Another limitation

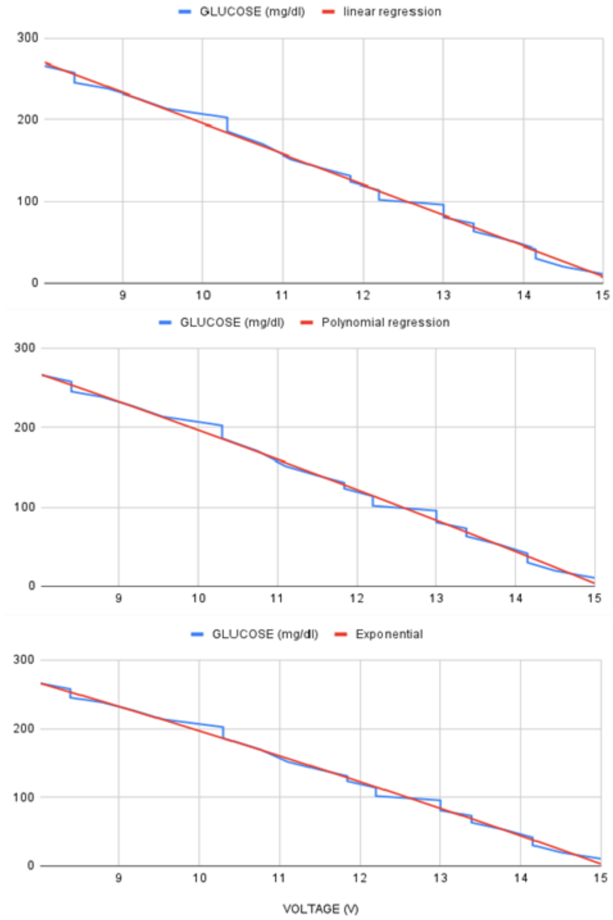

Fig.6. Comparison of glucose concentration using Linear regession (top), Polynomial regression (middle) and Exponential curve fitting (bottom)

is that the current non-invasive blood glucose monitoring methods are still in the research and development stage and are not yet widely available for use in clinical settings. In the proposed work, a non-invasive glucose measurement system is designed and setup. This system uses a dual-wavelength approach to measure glucose levels. The system takes into account the optical properties of glucose, Indian blue ink, titanium dioxide, and water solution. The properties of these substances depend on the wavelength of the incident light, which affects the light intensity measured by the detector. After careful experimentation, the optimal wavelengths for detecting glucose-level molecules in aqueous solutions have been determined to be 940 nm NIR and 630 nm red light radiations. These wavelengths have been chosen because they are able to penetrate the skin to a certain depth and have been shown to provide accurate measurements of glucose levels.

The output voltages of the sensor are expected to vary for different glucose concentrations. When the experiments are performed with varying glucose concentration solution, the photodetector output current drops from 0.40 mA to 0.21 mA, and the sensor output voltage drops from 15V to 8.02V. The sensor output voltages decrease as the glucose concentration increases. This outcome suggests that the decrease in light intensity detected by the detectors is due to the increase in light absorption at these wavelengths caused by the increase in glucose content. This finding is consistent with earlier studies and the Beer-Lambert law, which states that the amount of light absorbed by a material is proportional to its concentration. These results provide valuable insights for further development of the sensor design and its ability to accurately measure glucose levels. Nonetheless, additional research is required to validate the accuracy and reliability of the sensor across a range of glucose concentrations, and to evaluate its performance in clinical settings.

To further evaluate the relationship between the sensor output voltages and glucose concentrations, the Pearson correlation coefficient was used to measure the linear relationship between the average values of the normalised intensity and the glucose concentration values. The analysis of the data shows a significant correlation between the sensor output voltages and glucose concentrations, as evidenced by the high Pearson correlation coefficient (r) value of 0.9966 for the linear regression equation. This strong correlation indicates that the sensor can accurately measure changes in glucose concentrations. For the subsequent design and development stages of the non-invasive glucose optical sensor, the linear regression equation is chosen for calculating the unknown glucose concentration, which is expressed as:

$$y = -37.5877x + 571.2631 \qquad (2)$$

where y is glucose concentration (mg/dl) sensor output voltage (V) and x is sensor output voltage (V).

A comparison between the theoretical and experimental results are also conducted to evaluate the accuracy and reliability of the sensor under different conditions and to identify any potential sources of error or limitations. The concentration of glucose was measured non-invasively using the designed system, and a comparison was made with the gold standard, AccuCheck, which requires a specific strip to measure blood sugar levels. The mapping chart in Fig.7 shows a comparison between the glucose concentrations measured by the designed system and the glucometer. The chart shows a good correlation between the concentration values obtained by the designed system and those obtained by the glucometer. This indicates that the designed system is capable of accurately measuring glucose concentrations non-invasively.

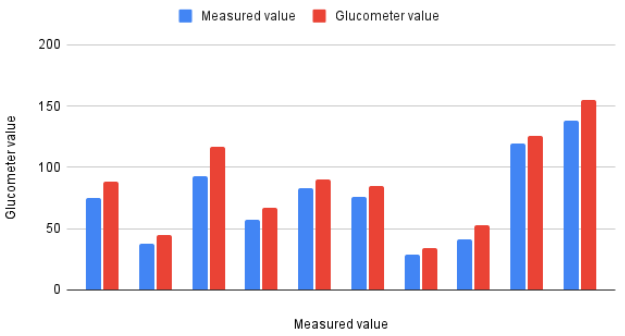

Fig. 7. Comparison with Glucometer readings and the measured values from the experimental setup

The ability to measure glucose concentrations non-invasively is particularly significant for individuals with diabetes who need to monitor their blood sugar levels regularly. Non-invasive measurement eliminates the need for repeated finger pricks and can help improve compliance with glucose monitoring, ultimately leading to better diabetes management. The good correlation between the designed system and the glucometer also suggests that the designed system has the potential to be used as an alternative to the traditional invasive method of glucose monitoring. Further studies are needed to evaluate the accuracy and reliability of the designed system under different conditions and to validate its effectiveness in managing diabetes.

5. Conclusion

The present article provides a brief overview of a non-invasive optical technique for measuring glucose levels using near-infrared and red light. The results demonstrate a good correlation between the measurements obtained from the glucometer and those obtained from the designed system. This suggests that NIR-based non-invasive blood glucose measurement technology is a viable option for accurately measuring glucose concentrations. However, the accuracy of non-invasive glucose monitoring using NIR spectroscopy can be affected by various factors such as skin pigmentation, temperature, and moisture content. Therefore, to improve the technology and ensure reliable and accurate glucose measurements, further research is needed. One possible way to improve the system's performance is to develop an appropriate signal conditioning circuit that can reduce interferences and enhance the signal-to-noise ratio.

Overall, non-invasive glucose monitoring has the potential to significantly improve the quality of life of people with diabetes by eliminating the need for repeated finger pricks. With further research and development, non-invasive glucose monitoring technology may become a viable alternative to traditional invasive methods of glucose monitoring, leading to better diabetes management and improved health outcomes.

Author contributions

Sivakumar Ramachandran: Conceptualization, Methodology, Writing-Reviewing and Editing.

Aiswarya Prakash: Conceptualization, Methodology, Writing-Original draft preparation, Software, Validation, Field study

Bejoy Abraham: Writing-Reviewing and Editing.

Biju VG: Writing-Reviewing and Editing

Conflicts of interest

The authors declare no conflicts of interest.

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