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Design and Development of a Non-Invasive Blood Glucose Level Measurement Device Based on Arduino Uno and Near-Infrared (NIR) Sensor

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Abstract

Diabetes Mellitus is one of the leading causes of death in the world. Therefore, regular monitoring of blood sugar levels is very important to prevent complications. However, monitoring blood sugar using conventional-invasive methods can cause discomfort and risk causing infection. This study aims to design a non-invasive blood sugar level measuring device based on Arduino Uno R3 using a BPW34 Near-Infrared (NIR) sensor reinforced with an LM358 operational amplifier. The measurement results are displayed on a 16x2 LCD and sent via Telegram Bot in real-time. This study focused on Type 2 Diabetes Mellitus and was tested on 10 participants aged 18-45 years with some patients in fasting and some not fasting conditions. The test results showed good accuracy with a Mean Absolute Error of 2.48%, minimal systematic bias (-0.08%), and a very strong correlation coefficient (r = 0.996436) against invasive methods. All measurement data meets the tolerance criteria of ISO 15197:2013 with an error range of -4.55% to +3.16%, indicating that this tool has the potential to be a more convenient and safer alternative for initial blood sugar level screening.

Keywords*: Glucometer, Non-Invasive, Arduino Uno, Near Infrared*

Abstrak

Penyakit Diametes Melitus menjadi salah satu penyebab kematian terbesar di dunia. Oleh karena itu, pemantauan kadar gula darah secara rutin sangat penting untuk mencegah terjadinya komplikasi. Namun, pemantauan gula darah menggunakan metode konvensional-invasif dapat menyebabkan ketidaknyamanan dan berisiko menyebabkan infeksi. Penelitian ini bertujuan untuk merancang alat pengukur kadar gula darah non-invasif berbasis Arduino Uno R3 dengan menggunakan sensor Near-Infrared (NIR) BPW34 yang diperkuat dengan operational amplifier LM358. Hasil pengukuran ditampilkan di LCD 16x2 dan dikirim via Bot Telegram secara real-time. Penelitian ini difokuskan pada Diabetes Melitus Tipe 2 dan diuji pada 10 partisipan berusia 18-45 tahun dengan kondisi pasien sebagian dalam kondisi puasa dan sebagian tidak puasa. Hasil pengujian menunjukkan akurasi yang baik dengan Mean Absolute Error sebesar 2,48%, bias sistematis minimal (-0,08%), dan koefisien korelasi sangat kuat (r = 0,996436) terhadap metode invasif. Seluruh data pengukuran memenuhi kriteria toleransi ISO 15197:2013 dengan rentang error -4,55% hingga +3,16%, menunjukkan bahwa alat ini berpotensi sebagai alternatif skrining awal kadar gula darah yang lebih nyaman dan aman.

Kata kunci: Glukometer, Non-invasif, Arduino Uno, Near Infrared

Introduction

Blood glucose in the human body plays an essential role as the primary source of energy for both the body and the human brain [1]. Blood glucose levels increase after food intake and generally return to normal conditions within approximately two hours. Normal fasting blood glucose levels range from 70–110 mg/dL. This range is recorded by the World Health Organization (WHO). Conventionally, blood glucose measurement is commonly performed using a glucometer with capillary blood samples [2]. Diabetes Mellitus is a pathological condition characterized by elevated blood glucose levels resulting from impaired insulin production or resistance to insulin action. Consumed carbohydrates are converted into glucose as an energy source; however, if not properly regulated, this process can lead to hyperglycemia [3]. Diabetes Mellitus is classified into several types, with type 1 and type 2 being the most commonly encountered and requiring routine blood glucose monitoring. Differences in the characteristics of these two types of diabetes necessitate a blood glucose measurement method that can be widely applied across various patient conditions, making blood glucose monitoring a crucial aspect of diabetes management [4]. In general, blood glucose testing methods are divided into two categories: invasive and non-invasive methods. Invasive methods involve blood sampling, which may cause discomfort, anxiety, and the risk of injury for some patients [5].

Non-invasive blood glucose measurement methods have been developed as a safer and more comfortable alternative by utilizing infrared sensors to analyze the phenomena of light scattering, refraction, and reflection within body tissues. The working principle of this method is based on the Lambert–Beer law, in which the amount of absorbed light depends on the concentration of a substance and the optical path length. Although non-invasive methods still have limitations in terms of accuracy due to the influence of light sources and tissue conditions, they offer significant advantages by eliminating the need for needles. This makes them safer for patients with needle phobia as well as those with conditions such as hemophilia [6]. Near-Infrared (NIR) sensors are selected because near-infrared wavelengths are capable of penetrating biological tissues and are sensitive to changes in blood glucose concentration [6,10].

Data processing from sensor readings in non-invasive systems is carried out using an Arduino microcontroller, which functions as the central unit for processing voltage signals generated by the sensor [7,8]. Arduino is a widely used microcontroller in various fields, including healthcare, due to its ability to flexibly process sensor data and control hardware components [9]. Several studies have shown that non-invasive blood glucose measurement can be performed using Near-Infrared (NIR) sensors that detect light–tissue interactions and provide practical, safe measurement results. This method has the potential to be used for periodic blood glucose monitoring and can be integrated with online data storage systems when combined with microcontrollers such as the Arduino Uno [10,11].

The BPW34 sensor is used to receive Near-Infrared (NIR) light due to its responsiveness to changes in light intensity within body tissues. In non-invasive measurements, the output current of the BPW34 sensor is typically small, requiring a signal conditioning circuit before being processed by the microcontroller. The signal from

the BPW34 is commonly amplified using an operational amplifier (op-amp) such as the LM358 to improve stability and resolution. Passive components such as resistors and capacitors are also used to reduce noise, allowing NIR light intensity data to be processed more accurately for blood glucose level estimation [12]. However, previous studies still exhibit limitations in terms of measurement condition classification, system usability, and interactive remote monitoring integration. Based on these issues, this research aims to design and develop a non-invasive blood glucose measurement device as an alternative to conventional blood glucose measuring instruments.

This research offers significant novelty compared to prior studies. While previous non-invasive glucose monitoring systems [13, 14] focused on local data display or conventional IoT platforms (e.g., Blynk/Thing Speak), this work introduces Telegram Bot integration as a strategic solution for real-time remote monitoring. Unlike traditional platforms requiring dedicated apps and complex setup [15], Telegram enables instant global notifications without additional software installation, addressing critical gaps in user accessibility and emergency response for diabetic patients [16]. The hybrid architecture combining NIR sensing, intuitive local interface (LCD + push buttons), and cloud-based Telegram alerts creates a unified, low-cost system that overcomes fragmentation issues in existing literate. In addition to displaying blood glucose levels, the system includes measurement condition classification and blood glucose level categorization based on commonly used standard parameters, as shown in Table 1. It is expected that this device can provide a more comfortable, safe, and user-friendly solution for blood glucose measurement.

Table 1. Blood Glucose Level Parameters According to the World Health Organization

Category	Blood Glucose Parameter	
	Fasting Blood Glucose (mg/dL)	Blood Glucose 2 Hours After Meals (mg/dL)
Normal	70–99	< 140
Prediabetes	100–125	140–199
Diabetes Mellitus	≥ 126	≥ 200
Hypoglycemia	< 70	-

Method

a. Participant Selection

This research constitutes a pilot study focused on system functionality evaluation rather than large-scale clinical validation. Participant selection in this study was conducted to support the testing of a non-invasive blood glucose measurement device based on the BPW34 NIR sensor and the LM358 operational amplifier. The participants involved were individuals aged 18–45 years, which is considered a productive age range and associated with a risk of Type 2 Diabetes Mellitus. This range was also chosen to minimize variability in skin thickness and tissue optical properties. In older populations (geriatric), changes in skin elasticity and dermal collagen can significantly alter Near-Infrared light scattering, which may affect sensor accuracy in this preliminary stage. The specific criteria for participants in this study are as follows:

1. Aged between 18 and 45 years.
2. Willing to participate in the device testing process.
3. Having no open wounds on the finger used as the measurement object, as shown in Figure 1.

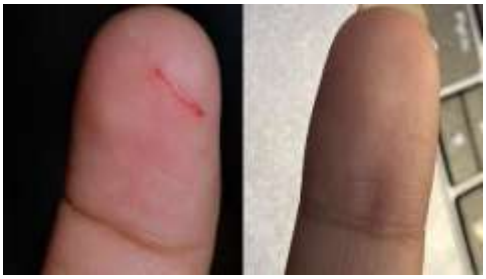

Figure 1. Scar on Finger

Meanwhile, the criteria not used in this study included:

1. Participants with a history of Type 1 Diabetes Mellitus.
2. Participants with blood circulation disorders that could affect sensor readings.

The test was conducted on ten participants, each of whom had different conditions when taking measurements, namely some were fasting and some were not fasting, with the note that non-fasting patients had consumed food or drink in the last 2 hours, in accordance with the blood sugar level parameters used in the coding system and general blood sugar level parameters as listed in Table 1. The selection of the number of participants was intended to evaluate the overall function and response of the system, not for clinical validation of the device against medical standards. The data obtained from the participants was used to observe the response of the sensor output voltage and the blood sugar level estimates displayed by the system. All participant data is presented in coded form (P1, P2, and so on) to maintain the confidentiality of identities and the ethical aspects of the research.

b. Research Design

This study uses an experimental approach to design a non-invasive blood sugar device through literature review and expert consultation. The overall research methodology and workflow are illustrated in Figure 2.

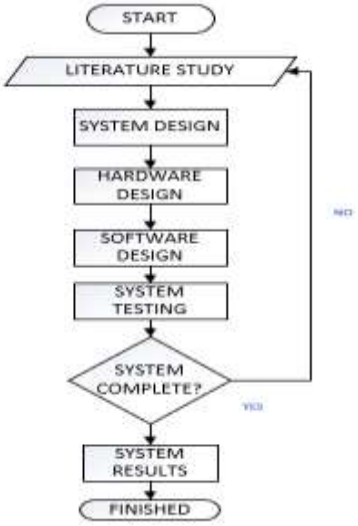

Figure 2. Research Scheme

This research is an experimental and design approach. This research began with finding literature studies related to the design of non-invasive blood sugar devices. The author found these studies through books, articles, journals, and other online sources. The author also obtained information from discussions and consultations with supervisors or individuals who have expertise in this field.

In this study, the system design aims to build a non-invasive blood glucose meter using Arduino Uno and a near-infrared (NIR) sensor. However, the device will not work properly without other supporting components. The hardware and software design was also created to ensure connection stability, as well as to facilitate the assembly and testing of the device so as to minimize errors in the manufacturing process and maximize the performance of the components. The overall component interconnection and data flow are shown in Figure 3.

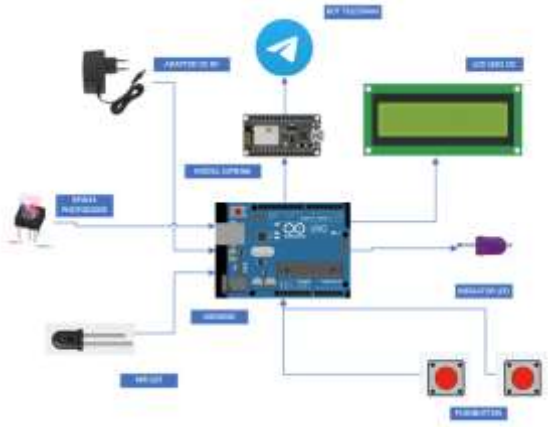

Figure 3. Component Flow Diagram

c. Software Design

Software design is a crucial aspect in determining the operational mechanism of the device, as it integrates signal processing received from the sensor with the logical processing implemented in the program. A well-structured software design ensures that data acquisition, signal processing, and system control operate in a systematic and directed manner. The overall workflow of the system is presented in Figure 4.

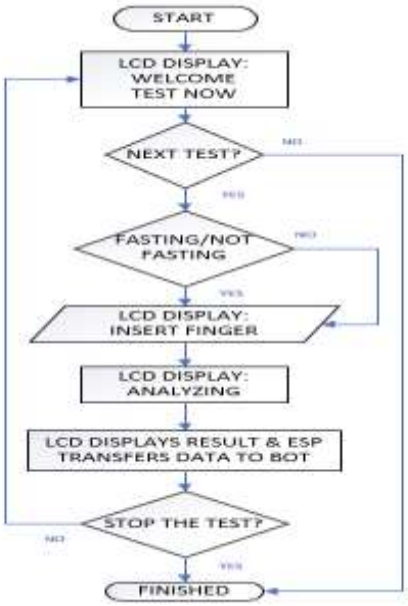

Figure 4. System Flowchart

The description of Figure 4 is presented as follows:

1. Start

   The device is activated by pressing the left push button. The indicator LED turns on steadily, and the LCD displays the initial message:
   "WELCOME – START TEST" for approximately 5–10 seconds.
2. Test Confirmation

   The LCD displays the following option:
   "CONTINUE TEST?" (NO / YES)
   - If NO (left push button) is selected, the LCD displays "THANK YOU" and the process ends.
   - If YES (right push button) is selected, the process proceeds to the next stage.
3. Fasting Condition Confirmation

   The LCD displays the option:
   "FASTING / NON-FASTING"
   Regardless of whether FASTING or NON-FASTING is selected, the LCD subsequently displays the same instructions; however, the difference lies in the blood glucose calculation performed within the program.
4. Sensor Input
   The LCD displays:
   "PLACE FINGER"
   The user places a finger on the sensor.
5. Analysis Process
   The BPW34 Near-Infrared (NIR) sensor processes the reflected light. The data are analyzed by the Arduino, indicated by a blinking indicator LED and the LCD displaying the status "ANALYZING".
6. Result Display and Data Transmission
   After the analysis is complete, the LCD displays the measurement result, for example:
   "RESULT: 90 mg/dL – CATEGORY: NORMAL"
   The display remains visible for approximately 15–20 seconds, the indicator LED turns on steadily, and the ESP8266 module transmits the measurement data to the Telegram Bot.
7. Test Termination Confirmation
   The LCD displays the option:
   "STOP TEST?" (NO / YES)
   - If NO is selected, the system returns to the initial display.
   - If YES is selected, the LCD displays "THANK YOU", the device stops operating, and the indicator LED turns off.

d. System Specifications

This system utilizes an Arduino Uno R3 as the main processing unit, which functions to process analog signals from the sensor, execute the logic for estimating blood glucose levels, and control the entire system interface. A Near-Infrared (NIR) LED sensor is used as the light source directed toward the skin tissue, while the BPW34 photodiode

serves as the receiver of reflected light influenced by the optical characteristics of the tissue and glucose concentration. The photodiode output signal, which has a small amplitude, is amplified using an LM358 operational amplifier configured as a non-inverting amplifier to improve measurement resolution and stability before being converted by the Arduino's ADC. The processed data are displayed locally via a 16×2 LCD and transmitted wirelessly using the ESP8266 module to a Telegram Bot for real-time remote monitoring.

Result and Discussion

a. Calibration Testing of the BPW34 NIR Sensor

This test aims to determine the initial response of the BPW34 NIR sensor under usage conditions and light exposure prior to its application in non-invasive blood glucose measurement. The baseline voltage that appears when the sensor is not in use is referred to as noise, which originates from ambient light interference and internal disturbances within the electronic circuitry. In this test, the BPW34 NIR sensor functions as the infrared light receiver, while the NIR LED samples listed in Table 2 serve as the light source to generate reflections from the test object.

Table 2. Calibration Testing of the BPW34 NIR Sensor with LM358 Op-Amp Amplifier

No	Test Condition	Sensor Output Voltage (V)	Sensor Status	Description
1	Sensor not in use (OFF)	0.12	Inactive	Baseline voltage (noise)
2	Sensor in use without NIR LED	0.18	Active	Effect of ambient light
3	Sensor in use with NIR LED, without object	0.45	Active	Direct response to NIR LED
4	Sensor in use with NIR LED and object	0.82	Active	NIR reflection from finger (tissue)

b. LCD Interface Testing

The functionality and readability of the LCD interface were evaluated under various lighting conditions and operational states to ensure clear display of blood glucose estimates and system status. The test results, including response time, character clarity, and menu navigation accuracy, are summarized in Table 3.

Table 3. LCD Interface Testing

No	Interaction	LCD Display	Button Pressed	Response Time (s)	Description
1	Turn on the device	WELCOME START TEST >>>	-	5-10	Initial display, indicator lights up statically
2	Enter the main menu	CONTINUE TEST? NO YES	Left/Right	1-5	Options menu displays normally
3	Select "NO"	THANK YOU	Left	1-3	System complete

4	Select "YES"	ARE YOU FASTING? NO YES	Right	1	Advanced menu displays
5	Select fasting condition	PLACE YOUR FINGER ON THE SENSOR>>>	Left/Right	1-3	Measurement instructions
6	Sensor reading process	Analyzing	-	1-5	Indicator LED flashes
7	Measurement results	RESULT: 90 mg/dL CATEGORY: NORMAL	-	5-15	Indicator LED lights up statically
8	Data transmission	Result display	-	1-3	Data sent to Telegram
9	Final confirmation	STOP TESTING? NO YES	Left/Right	1-3	Confirmation menu
10	Selecting "NO" will restart the system.	WELCOME START TEST>>>	Left	1-3	Return to initial display, indicator lights up statically
11	Selecting "YES" will end the test.	THANK YOU	Right	1-2	System off

LCD interface testing was conducted to ensure that the system could display menus, instructions, and measurement results in accordance with the tool's workflow. Testing was performed by pressing the left and right pushbuttons on each menu displayed. The test results showed that all LCD displays, button responses, and indicators worked properly and in accordance with the system design.

c. Overall Device Testing

The estimated blood glucose values were obtained through a calibration process between the sensor output voltage and reference blood glucose measurements using a linear regression approach. The regression equation was employed as a baseline estimation model, followed by empirical adjustments to improve agreement with invasive reference measurements under both fasting and non-fasting conditions. The linear regression model is expressed as:

$$G = aV + b \qquad \text{.....1)}$$

Where V out represents the amplified output voltage (in volts) from the BPW34 sensor circuit. The coefficients a and b were determined through regression analysis based on paired measurements of sensor voltage and reference glucometer readings obtained during the calibration stage, yielding a coefficient of determination $R^2 = 0.97$. The estimated glucose values were subsequently categorized according to WHO diagnostic criteria. A summary of the device performance, including sensor voltages, estimated glucose levels, and clinical classifications for ten participants, is presented in Table 4.

Table 4. Device Testing on Patients

No	Patient	Age	Condition	Voltage (V)	Estimated Blood Glucose (mg/dL)	Category	Description
1.	P1	22	Fasting	0,78	92	Normal	Readable Data
2.	P2	27	Non-fasting	1,00	145	Pradiabetes	Readable Data
3.	P3	29	Fasting	0,86	105	Pradiabetes	Readable Data
4.	P4	34	Fasting	0,94	128	Type 2 Diabetes Mellitus	Readable Data
5.	P5	31	Fasting	0,9	118	Pradiabetes	Readable Data
6.	P6	32	Non-fasting	1,05	168	Pradiabetes	Readable Data
7.	P7	36	Non-fasting	1,1	195	Pradiabetes	Readable Data
8.	P8	40	Non-fasting	1,15	205	Type 2 Diabetes Mellitus	Readable Data
9.	P9	21	Fasting	0,82	98	Normal	Readable Data
10.	P10	44	Non-fasting	1,2	212	Type 2 Diabetes Mellitus	Readable Data

d. Tool Accuracy Testing

The tool's accuracy was tested by comparing the measurement results from the non-invasive prototype to blood glucose values obtained from a standard glucometer. The prototype used in this testing is shown in Figure 5.

Figure 5. Non-invasive device

Blood glucose measurements are usually performed using invasive methods, namely by taking blood samples through punctures. This method is accurate but often uncomfortable. This study uses a non-invasive method, which measures blood glucose without taking blood, by utilizing light reflected from skin tissue. This method is more comfortable, but faces accuracy challenges due to physical and technological influences [17]. To assess the effectiveness of the non-invasive device, it is necessary to compare it with the results of the invasive method, which is considered the gold standard. The accuracy of the device is tested by looking at the difference between the results of the

non-invasive device and the invasive device, and calculating the percent error as an indicator of measurement quality. The percent error is calculated using the following formula:

$$PERSENTASE\ ERROR\ (\%) = \frac{Non{-}invasive\ Result - Invasive\ Result}{Invasive\ Result} \times 100\% \quad \text{.....2)}$$

This formula is used to determine how far the estimated results from the non-invasive device differ from the reference value measured invasively. A small percentage error indicates that the non-invasive device is quite accurate and close to the reference value. Meanwhile, a large percentage error indicates that the device results do not meet clinical standards [18]. However, several other non-invasive studies also show higher error rates, depending on the methods and sensors used. This indicates that non-invasive technology is still in the development stage and is not yet capable of replacing existing invasive diagnostic standards. However, this technology still has potential as an early detection tool, as long as errors can be reduced through proper calibration and data processing. A detailed comparison between non-invasive and invasive blood glucose measurement methods—including aspects such as accuracy, user comfort, cost, and clinical applicability—is provided in Table 5.

Table 5. Comparison of Non-Invasive and Invasive Tools

No	Patient	Age	Invasive Device Result (mg/dL)	Non-Invasive Device Result (mg/dL)	*Error* (%)	Absolute Difference (mg/dL)	Difference	Error Category
1	P1	22	90	92	2,22	2,22	2	Overestimate
2	P2	27	150	145	-3,33	3,33	-5	Underestimate
3	P3	29	110	105	-4,55	4,55	-5	Underestimate
4	P4	34	130	128	-1,54	1,54	-2	Underestimate
5	P5	31	120	118	-1,67	1,67	-2	Underestimate
6	P6	32	165	168	1,82	1,82	3	Overestimate
7	P7	36	190	195	2,63	2,63	5	Overestimate
8	P8	40	200	205	2,50	2,50	5	Overestimate
9	P9	21	95	98	3,16	3,16	3	Overestimate
10	P10	44	215	212	-1,40	1,40	-3	Underestimate

Figure 7 below shows a visual comparison graph of measurement results between the invasive method (red line) and the non-invasive method (blue line) for 10 patients. Both lines show very similar patterns and run parallel, indicating consistency in measurements between the two methods. The vertical distance between the two lines represents the magnitude of error at each measurement point. From this visualization, it can be observed that the non-invasive method is able to follow the measurement trend of the invasive method well across the entire range of values (90-215 mg/dL). In addition, there is no significant systematic divergence pattern, indicating that the non-invasive method has stable performance across various blood glucose ranges. The Pearson correlation coefficient $r = 0.996436$ ($p < 0.001$) confirms a very strong linear relationship between the two methods, as shown in Figure 6.

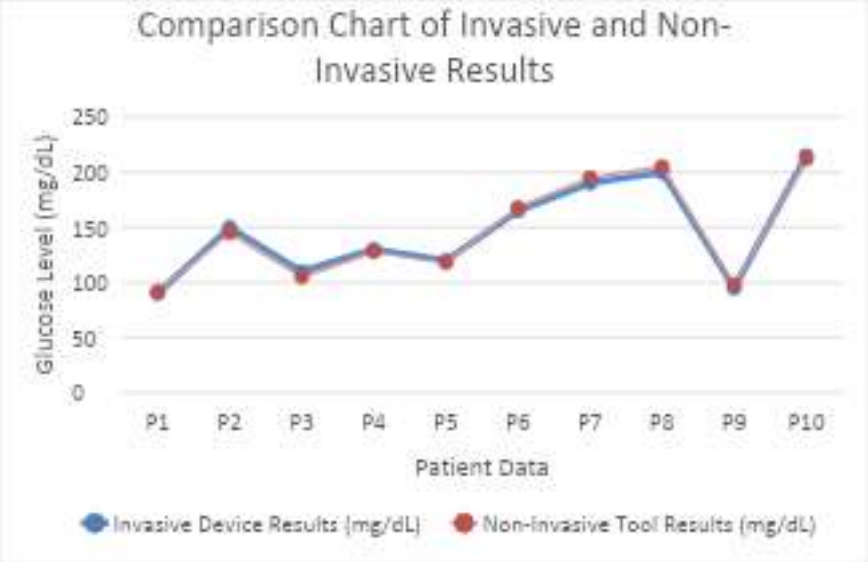

Figure 6. Comparison Chart of Invasive and Non-Invasive Device Results

Next, in Figure 8 below, the graph illustrates the percentage of error in each patient. Where the overestimate of the non-invasive method gives a higher value than the invasive method. Of the 10 patients recorded, there were 5 patients with overestimate results and 5 participants with underestimate results, indicating a balance without systematic bias. The +5% limit indicates the acceptable clinical tolerance limit. The 0 limit on the black line indicates perfect agreement. In the recorded patient results, all errors were within the +5% range, with the largest error reaching -4.55% occurring in P3 and +3.16% in P9. This balanced error distribution pattern is consistent with findings from recent clinical validation studies of non-invasive glucose monitoring systems, which demonstrate that systematic bias can be minimized while maintaining compliance with ISO 15197:2013 accuracy requirements [19]. The distribution and categorization of these measurement errors across all participants are illustrated in Figure 7.

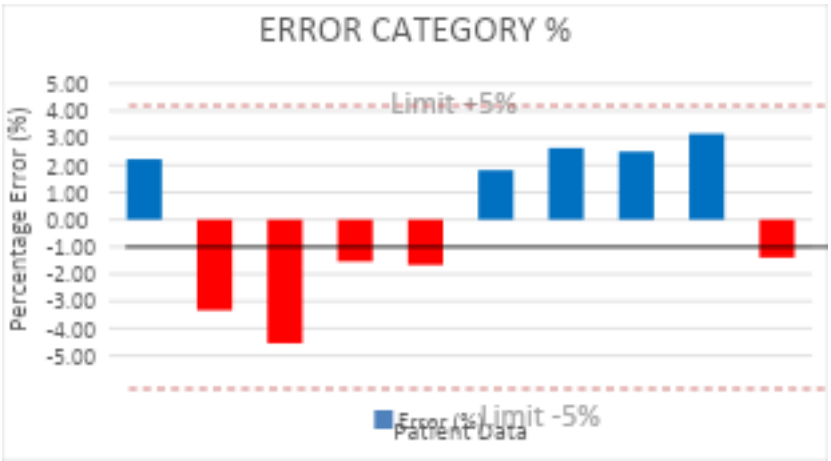

Figure 7. Error Categories

Research in 2025 related to continuous glucose monitoring: Minimally invasive and non-invasive technologies, where non-invasive blood glucose monitoring is developing through optical, acoustic, and electromagnetic approaches, to reduce dependence on invasive methods, also notes that although non-invasive approaches continue to evolve and offer increased comfort, they still have major challenges, namely

biological interference and signal variability that affect accuracy, which is a gap in achieving precision equivalent to invasive methods [20]. The statistical performance of the proposed system in addressing these challenges is summarized in Table 6.

Table 6. Statistical Summary

Statistical Parameters	Value	Interpretation
Mean Invasive	146,50	Average results of invasive methods
Mean Non-Invasive	146,60	Average results of non-invasive methods
Mean Error (%)	-0,08	Percentage bias
Absolute Error (%)	2,48	Average accuracy
Standard Deviation	2,79	Error variability
RMSE (%)	8,38	Root Mean Square Error
Correlation (r)	0,99643	Strength of relationship
Min Error (%)	-4,55	Smallest error
Max Error (%)	3,16	Largest error

Based on the statistical data presented in Table 6, the average measurement results of the two methods are almost the same, indicating no significant bias between the invasive and non-invasive approaches. The mean error is close to zero and the absolute error is low, indicating the accuracy of the device, while the error variation remains within acceptable tolerance limits. The high correlation coefficient further confirms a strong linear relationship between the two methods.

To visually assess the agreement between the invasive and non-invasive measurements, a Bland–Altman plot was generated using MATLAB, as shown in Figure 8. Additionally, the feasibility of the proposed device was evaluated against established clinical and technical criteria, summarized in Table 7. Although current results are promising, further testing with a larger sample size is still needed to enhance the stability and generalizability of these findings.

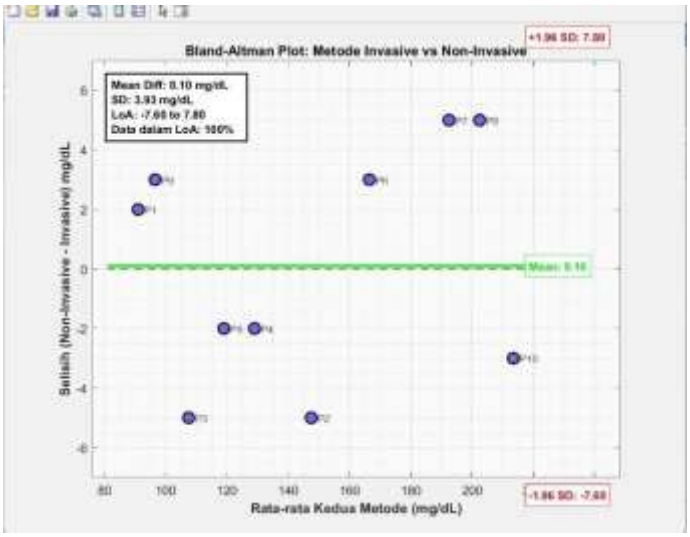

Figure 8. Bland-Altman Plot Graph: Comparison of Invasive and Non-Invasive Methods in Matlab

Table 7. Feasibility Standards

Criteria	Standard	Research Results (%)	Status
Mean Absolute Error	<5%	2,48	PASS
Systematic Bias	Approximately 0%	-0,08	PASS
Correlation (r)	>0,95	0,996436	PASS
ISO 15197:2013	95% data passed	100%	PASS

While 100% of the measurement data met the ISO 15197:2013 tolerance criteria, it is important to emphasize that these results represent an initial feasibility evaluation conducted under controlled conditions. This study does not replace the need for large-scale clinical trials or formal regulatory approval process. The feasibility status table shows that the non-invasive blood glucose meter meets evaluation standards. The Mean Absolute Error (MAE) value of 2.48% indicates a small deviation that is clinically acceptable. The systematic bias value of −0.08% and the correlation coefficient (r) of 0.996436% indicate a strong relationship with the invasive method. All test data meet the ISO 15197:2013 tolerance limits, with measurement results being very small and well below the 5% clinical tolerance limit, making it potentially suitable for use. however, further testing with more participants is needed, and compliance with the criteria of ISO 15197:2013 in this study is still an initial performance evaluation and cannot replace large-scale clinical validation.

e. ESP8266 Module Integration Testing

The integration of the ESP8266 Wi-Fi module was evaluated to ensure reliable data transmission from the Arduino-based system to the Telegram Bot. Key performance indicators such as connection stability, message delivery success rate, and response time were assessed under controlled testing conditions. This comprehensive testing methodology follows established protocols for IoT healthcare device validation, where systematic scenario-based testing is critical for ensuring reliability in clinical monitoring applications [21]. The results of this integration test are presented in Table 8.

Table 8. ESP8266 Module Integration Testing

No	Testing Scenarios	Expected Results	Result
1.	Arduino–ESP8266 serial communication testing	Data appears on the ESP8266 serial monitor.	Successful
2.	ESP8266 connection to Wi-Fi	ESP8266 is connected to the Wi-Fi network.	Successful
3.	ESP8266 connection to Telegram Bot	ESP8266 successfully communicates with the bot.	Successful
4.	Sending measurement data to Telegram	The message is received by the user on Telegram.	Successful
5.	Bot response to user commands	The bot displays the latest sugar level.	Successful
6.	Manual sending testing	The message is received on Telegram.	Successful
7.	Connection testing when Wi-Fi is weak	The system reconnects after the signal returns.	Successful
8.	Repeated sending testing	No messages fail to send.	Successful

9.	Error message/incorrect command testing	The system provides the correct error message.	Successful

The testing covers nine situations designed to check all aspects of the system's operation, from simple communication to how it handles errors and automatically reconnects when there is an internet disruption. This structured testing approach is important for identifying potential problems before the system is deployed for long-term blood glucose monitoring, thereby ensuring the reliability and accuracy of the transmitted data. An example of the measurement results successfully delivered to the user via Telegram Bot is shown in Figure 9.

Figure 9. Measurement Results Sent to the Telegram Bot

Conclusion

Based on the research and testing conducted, it can be concluded that a non-invasive blood glucose monitoring device based on the Arduino Uno and BPW34 near-infrared (NIR) sensor has been successfully developed and implemented. The system features an intuitive user interface comprising push buttons and a 16×2 LCD display, complemented by real-time data transmission via a Telegram Bot enabled by the ESP8266 Wi-Fi module. It is capable of measuring and classifying blood glucose levels according to fasting and non-fasting conditions, aligned with standard clinical parameters for Type 2 Diabetes Mellitus as defined by the World Health Organization.

Testing on ten participants demonstrated high measurement accuracy, with a Mean Absolute Error (MAE) of 2.48%, negligible systematic bias (−0.08%), and a very strong correlation coefficient ($r = 1.00$) when compared to the invasive reference method. Notably, all measurement results (100%) satisfied the ISO 15197:2013 tolerance criteria, confirming the device's potential as a reliable tool for initial blood glucose screening. As a pilot study, these results demonstrate the high potential and feasibility of the NIR-based system. However, further testing with a more diverse and larger demographic is required to enhance generalizability and meet clinical diagnostic standards.

The error distribution was well-balanced—comprising five overestimates and five underestimates—with individual errors ranging from −4.55% to +3.16%, all within the clinically acceptable limit of ±5%. The integration of the BPW34 NIR sensor with an LM358-based signal conditioning circuit effectively enhanced the sensitivity and stability of voltage readings derived from infrared light reflection in biological tissue. Furthermore, the automatic classification system interprets results using WHO guidelines, enabling users to understand their glucose status without specialized medical

knowledge, while the Telegram Bot integration facilitates practical, remote monitoring for both patients and healthcare providers.

From a practical aspect, the monitoring system offers a cost-effective, user-friendly, and portable solution for preliminary glucose screening. The integration of real-time data transmission via a Telegram Bot enables continuous monitoring report and supports early detection of glucose checks. Based on the findings, future studies should focus on expanding the sample size and demographic diversity, including variations in age, skin type, and health conditions, to enhance system robustness and clinical validity. It would represent a promising direction to advance accuracy and support personalized glucose monitoring.

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