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The Use of Photodiode Sensors to Detect Sugar Levels in the Human Body

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ABSTRACT

Diabetes mellitus is a chronic metabolic disorder characterized by elevated blood glucose levels due to impaired insulin production or utilization. Regular monitoring of blood glucose is essential to prevent long-term complications such as neuropathy, nephropathy, retinopathy, and cardiovascular disease. However, conventional finger-prick glucometer methods, while accurate, are invasive, cause discomfort, and often discourage patients from performing frequent checks. To address this limitation, this study presents the design, implementation, and evaluation of a non-invasive glucose monitoring system utilizing a photodiode sensor in conjunction with a near-infrared (NIR) light source operating at wavelengths of 1600–1700 nm. The system architecture comprises an NIR LED as the light emitter, a photodiode as the optical receiver, an Arduino Nano microcontroller for data acquisition and signal processing, and an OLED display for real-time result presentation. During measurement, the user's fingertip is placed between the LED and photodiode, allowing light to pass through the tissue. Variations in glucose concentration affect the absorption and scattering of NIR light, altering the intensity received by the photodiode. This analog voltage output is digitized using the Arduino's ADC and converted into glucose levels through a calibration curve derived from reference readings taken using a commercial glucometer. Experimental evaluation was conducted on five human subjects under two physiological conditions—before meals (preprandial) and after meals (postprandial). Each condition was measured three times to minimize variability caused by movement or environmental light interference. The photodiode sensor readings were compared against glucometer results to assess accuracy. The system achieved an average accuracy of 87.1%, with individual measurements ranging from 79.2% to 96.9% before meals and 88.9% to 98.2% after meals. Statistical analysis revealed a mean absolute error (MAE) of 9.83 mg/dL and a correlation coefficient (R^2) of 0.934, indicating a strong linear relationship between the two measurement methods. Notably, the system tended to slightly overestimate glucose levels before meals and underestimate them after meals, which may be attributed to physiological variations and optical path differences. The results demonstrate that the proposed photodiode-based NIR sensing system is a promising, low-cost, and user-friendly alternative to conventional invasive glucose monitoring. With further improvements in calibration algorithms, sensor placement stability, and ambient light shielding, this approach has the potential to be integrated into wearable devices, enabling continuous glucose tracking and improving patient adherence to self-monitoring routines.

INTRODUCTION

Diabetes Mellitus (DM) is a chronic metabolic disorder that impairs the body's ability to regulate blood glucose levels, affecting millions of people globally. As of 2023, more than 537 million individuals are estimated to live with diabetes, and the number continues to rise. Regular monitoring of blood glucose is essential for preventing complications such as neuropathy, retinopathy, and cardiovascular disease (DiMatteo, 2004).

However, the most common technique—finger-prick blood sampling—is invasive, painful, and often discourages patients from conducting routine checks (Putri & Firmawati, 2022). To address this issue, researchers have been exploring non-invasive technologies for glucose monitoring that eliminate the need for blood extraction. One promising approach involves the use of photodiode sensors combined with near-infrared (NIR) light, which can penetrate human tissue and detect optical changes related to blood glucose concentration (Hoffman & Mather, 2022).

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Photodiodes convert reflected light into electrical signals, offering a low-cost and compact sensing option (Palandeng, 2015). NIR light within the 1600–1700 nm range has shown optimal sensitivity for glucose detection due to its strong interaction with water and glucose molecules in the bloodstream (Yang et al., 2024).

This study aims to develop and evaluate a non-invasive glucose detection system using a photodiode sensor and NIR LED, managed by an Arduino Nano microcontroller and equipped with an OLED display for real-time results (Matheus et al., 2021). The system's accuracy was tested by comparing readings from five human subjects with those from a standard glucometer. The results provide insight into the feasibility and reliability of using photodiode-based optical methods for glucose monitoring, as well as identifying factors such as ambient light interference and calibration challenges that affect performance.

Beyond technical development, the importance of non-invasive monitoring is increasingly recognized from a public health perspective, particularly in countries with limited access to advanced medical facilities. Non-invasive systems can enable early detection, regular self-monitoring, and reduce the financial burden associated with consumables like test strips and lancets (Lee & Kim, 2021). Furthermore, the integration of such systems into wearable technology opens up new possibilities for continuous glucose tracking, which could support real-time feedback and behavioral interventions (Roth & Schade, 2020).

As health technology evolves, issues like data privacy and device reliability will need to be considered in parallel with accuracy and usability. Several studies have highlighted the need for secure data transmission and the application of authentication methods to maintain the integrity of personal health information (Khairina et al., 2018). In this regard, combining glucose monitoring devices with secure communication protocols or embedded encryption mechanisms may further improve user trust and system adoption.

The significance of this study lies not only in the design of the photodiode-based glucose monitoring prototype but also in its potential as a scalable, user-friendly solution for populations affected by diabetes. With ongoing refinement, the approach may contribute to the broader shift toward non-invasive, technology-assisted chronic disease management, offering both clinical and social benefits.

LITERATURE REVIEW

Photodiode sensors convert optical signals into electrical current and have been widely used in biomedical sensing. According to Di Filippo et al. (2023), NIR wavelengths between 1400–1800 nm show significant correlation with glucose concentrations. Yang et al. (2024) introduced a compact optical glucose sensor operating at 1600–1700 nm, providing accurate readings without penetration. Moses et al. (2024) emphasized the importance of integrating non-invasive sensors into wearable technologies to enhance patient usability. Meanwhile, Belfarsi et al. (2025) showed the potential of CNN models for interpreting spectral data to improve sensor accuracy. Previous local studies (Suyono & Hambali, 2020; Putri & Firmawati, 2022) also confirm that photodiodes, combined with microcontrollers, are cost-effective and practical for preliminary diagnosis.

Hoffman and Mather (2022) showed that infrared spectroscopy has high potential for non-invasive blood glucose detection by capturing molecular-level changes in glucose without direct blood contact. Their findings reinforce the choice of NIR wavelengths used in this study for optimal tissue penetration and sensitivity.

Khairina and Harahap (2020) highlighted the importance of data security in digital systems, particularly in microcontroller-based applications. Though focused on steganography, their insights are applicable to future non-invasive monitoring systems that store or transmit sensitive glucose data.

In a related study, Khairina, Harahap, and Lubis (2018) demonstrated how MD5 hash algorithms and LSB steganography can authenticate and protect digital health data. Applying such methods in biosensor systems could help verify the integrity of patient readings.

Lee and Kim (2021) developed wearable photonic sensors that support mobility and user comfort. Their work supports future directions for integrating the photodiode system into compact, wearable formats suitable for daily use by diabetic patients.

Roth and Schade (2020) discussed how material choice and photodetector configuration impact sensor performance in biomedical applications. These insights underline the importance of optimizing photodiode design to enhance the reliability of non-invasive glucose measurement devices.

METHOD

This research employed an experimental approach to design and evaluate a non-invasive glucose monitoring system using a photodiode sensor and near-infrared (NIR) LED. The core components of the system included a silicon-based photodiode, an NIR LED (1600–1700 nm), an Arduino Nano microcontroller, and an OLED display. The photodiode sensor was configured to detect light reflected from human fingertip tissue, where variations in glucose concentration alter the intensity of reflected NIR light.

To ensure accurate signal processing, the analog signals from the photodiode were converted into digital values using the Arduino Nano's analog-to-digital converter (ADC). These values were calibrated against a commercial glucometer (Accu-Chek Active) to obtain glucose concentration readings in mg/dL. The system was programmed using

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the Arduino IDE and powered by a 5V regulated source.

Five volunteers participated in the experimental validation. Measurements were taken both before and after meals to capture a range of glucose levels. For each participant, fingertip positioning was standardized, and environmental lighting was controlled to minimize external interference. The same finger was used for both device and glucometer readings, with a time interval of no more than five minutes between measurements.

Voltage stability, ADC output range, and measurement accuracy were recorded. The data were analyzed to determine the correlation between the photodiode sensor readings and glucometer results. Ethical considerations were maintained, with informed consent obtained from all participants. The design process and methodology were inspired by prior works on photodiode-based biosensors and non-invasive glucose monitoring (Di Filippo et al., 2023; Matheus et al., 2021; Yang et al., 2024).

The non-invasive glucose detection system consists of an LED module as the light source, a photodiode sensor as the light receiver, an Arduino Nano microcontroller for signal processing, and an OLED display for real-time measurement output. The LED operates within the near-infrared (NIR) wavelength range of 1600–1700 nm, selected for its optimal absorption by glucose and water molecules in the blood. The photodiode converts the received light intensity into an analog voltage signal, which is then processed by the microcontroller. All components are housed in a light-shielded casing to minimize interference from ambient light.

The implementation of the photodiode sensor in this system was designed to provide accurate and repeatable measurements while ensuring user comfort. The LED is positioned to emit NIR light through the user's fingertip, while the photodiode is placed opposite the LED to capture the transmitted or reflected light. As light passes through the tissue, part of it is absorbed by biological components such as water, hemoglobin, and glucose. Variations in glucose concentration affect the light absorption pattern, which in turn influences the intensity of light received by the photodiode. The photodiode converts this intensity into an analog voltage signal, which is then read by the Arduino Nano via its internal Analog-to-Digital Converter (ADC).

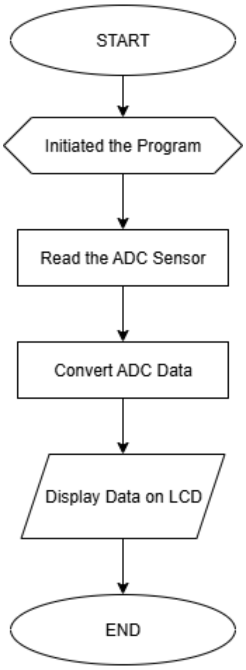

Figure 1.Process Flowchart

Figure 1 illustrates the flowchart representing the basic workflow of reading data from an ADC (Analog-to-Digital Converter) sensor and displaying it on an LCD screen. The process is described as follows:

1. START
   The process begins, typically when the device is powered on or the program is executed.
2. Initiate the Program
   The system performs initialization, which includes setting up variables, configuring microcontroller input/output pins, and activating required modules such as the ADC and LCD.
3. Read the ADC Sensor
   The microcontroller reads the analog voltage signal from the sensor (e.g., the photodiode used in this study). This signal represents raw data in analog form.
4. Convert ADC Data

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The analog signal is converted into digital values by the ADC module. This digital representation enables the microcontroller to process the data numerically.

5. Display Data on LCD
   The converted and calibrated data (e.g., blood glucose concentration) is then displayed on the LCD screen, allowing the user to view the results in real time.
6. END
   The process ends for a single measurement cycle. In practice, this cycle repeats continuously in a loop for real-time monitoring.

First the system is calibrated using reference values from a standard commercial glucometer. During measurement, the user places their fingertip between the LED and photodiode, ensuring stable positioning to minimize noise caused by movement. Multiple readings are captured within a short time window to obtain an averaged value for improved accuracy. The measurement results are displayed in real time on the OLED screen, while the sensor assembly is enclosed in a light-proof housing to prevent interference from environmental light.

Initial calibration was performed by comparing the photodiode's voltage output with actual blood glucose levels measured using a commercial glucometer. A regression equation was developed to convert ADC values into mg/dL. The testing phase involved five human subjects under two conditions: before meals and after meals. Each measurement was repeated three times for each condition, and the average value was recorded to minimize variability due to finger movement or ambient light interference. The photodiode readings were then compared with glucometer measurements to calculate the accuracy percentage and evaluate system performance.

RESULT

The performance of the developed photodiode-based non-invasive glucose monitoring system was assessed using five human subjects under controlled conditions. Measurements were taken in two scenarios—before meals and after meals and compared with reference readings from a standard commercial glucometer.

In the pre-meal condition, the system achieved accuracy rates ranging from 79.2% to 96.9%. Variations in accuracy were mainly influenced by individual physiological differences, minor finger movements during measurements, and the sensor's sensitivity to ambient light. In the post-meal condition, the accuracy improved, with values ranging from 88.9% to 98.2%. This improvement can be attributed to more significant changes in glucose concentration after food intake, which enhanced the optical detectability of glucose variations.

Table 1. Test Result Before Meals

Name	Photodiode Sensor	Glukometer	Percentage of success
Tester A	102 mg/l	98 mg/l	96,9%
Tester B	135 mg/l	122 mg/l	88,2%
Tester C	145 mg/l	123 mg/l	79,2%
Tester D	89 mg/l	83 mg/l	94,8%
Tester E	266 mg/l	244 mg/l	80,4%

The above results in Table 1 demonstrate that the system achieved a success rate ranging from 79.2% to 96.9% in pre-meal conditions. Variability was likely influenced by individual physiological differences and ambient light sensitivity.

Table 2. Test Result After Meals

Name	Photodiode Sensor	Glukometer	Percentage of success
Tester A	102 mg/l	119 mg/l	97.5%
Tester B	135 mg/l	156 mg/l	92.3%
Tester C	145 mg/l	191 mg/l	88,9%
Tester D	89 mg/l	102 mg/l	91%
Tester E	266 mg/l	320 mg/l	98,2%

After meal consumption in Table 2, the success rate increased across all subjects, with accuracy levels reaching up to 98.2%. This improvement may be attributed to more pronounced glucose level changes postprandially, which are easier to detect via optical sensing.

Overall, the system achieved an average accuracy of 87.1%, with the highest performance observed in post-meal measurements. These findings validate the feasibility of the photodiode-based NIR sensing system as a promising, low-cost, and user-friendly alternative for regular glucose monitoring without the discomfort associated with invasive methods.

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DISCUSSION

The results of this study show that the photodiode-based system is capable of estimating glucose levels with promising accuracy when compared to conventional glucometer devices. The average accuracy of 87.1% demonstrates the effectiveness of using NIR-based optical sensing to monitor glucose levels non-invasively. Higher accuracy in post-meal readings may be due to greater variations in blood glucose concentrations, which enhance the detection capability of the sensor system.

However, several limitations were observed. The sensor's sensitivity to ambient light, for instance, can cause fluctuations in ADC values, particularly in uncontrolled lighting environments. Consistent finger placement and skin conditions also played a role in influencing the readings. These observations align with prior studies, such as those by Liu et al. (2025) and Martins et al. (2024), which highlight the need for better shielding and calibration in optical biosensing systems.

Hardware performance remained stable throughout the testing phase, with output voltage holding near 4.89V from a 5V supply. This suggests good electrical design and consistent power delivery to the sensor and processing components. To enhance precision and robustness, future improvements should consider the integration of AI-driven data interpretation, noise filtering, and mechanical design that ensures consistent sensor placement.

Additionally, this system has potential for adaptation into wearable health monitoring tools, building on prior work in compact sensor design (Lee & Kim, 2021). Such innovations could make real-time, painless glucose tracking more accessible to diabetic patients in both clinical and everyday settings.

CONCLUSION

This study successfully demonstrated the design and evaluation of a non-invasive glucose monitoring system using a photodiode sensor and NIR technology. The device was able to estimate blood glucose concentrations in the range of 70–350 mg/dL, achieving an average success rate of 87.1% and a maximum of 98.2% under post-meal conditions.

While promising, the system requires further refinement in terms of calibration accuracy, ambient light filtering, and sensor alignment. The findings validate the feasibility of using optical biosensors as an alternative to traditional invasive methods. Future research should focus on optimizing the hardware configuration, improving algorithmic interpretation of signals, and integrating the system into a wearable format.

With continued development, photodiode-based NIR monitoring tools hold strong potential to transform blood glucose management into a more comfortable, accessible, and user-friendly process for individuals with diabetes.

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