

**NEAR-INFRARED GLUCOSE SENSING IN
ADULTERATED HONEY USING SMARTPHONE-
BASED PHOTOMETRIC DETECTION: A
FEASIBILITY STUDY**

MUHAMMAD ALIF DANIAL BIN MOHD NAZIR

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FEASIBILITY STUDY**

by

MUHAMMAD ALIF DANIAL BIN MOHD NAZIR

**Dissertation submitted in partial fulfilment of the requirements for degree of Bachelor
of Health Sciences (Honours) (Medical Radiation)**

July 2025

CERTIFICATE

This is to certify that the dissertation entitled **“NEAR-INFRARED GLUCOSE SENSING IN ADULTERATED HONEY USINGSMARTPHONE-BASED PHOTOMETRIC DETECTION: A FEASIBILITY STUDY”** is the bona fide record of research work done by **MUHAMMAD ALIF DANIAL BIN MOHD NAZIR** during the period from October 2024 to June 2025 under my supervision. I have read the dissertation and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation to be submitted in partial fulfilment for the degree of Bachelor of Health Science (Honours) (Medical Radiation)

Main supervisor,

.....

Dr Muhammad Nur Salihin Yusoff

University Lecturer School of Health Sciences

Universiti Sains Malaysia

Health Campus

16150 Kubang Kerian Kelantan,

Malaysia

Date: 26 July 2025

DECLARATION

I hereby declare that this dissertation is the result of my own investigation, except where otherwise stated and duly acknowledged. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at Universiti Sains Malaysia or other institutions. I grant Universiti Sains Malaysia the right to use the dissertation for teaching, research, and promotional purposes.

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MUHAMMAD ALIF DANIAL BIN MOHD NAZIR

Date: 26 July 2025

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**PENGESANAN GLUKOSA INFRARED DEKAT DALAM MADU TIRUAN
MENGUNAKAN PENGESANAN FOTOMETRI BERASASKAN TELEFON
PINTAR: KAJIAN KEBOLEHAN**

Abstrak

Pengesanan glukosa adalah penting dalam kesihatan seperti pemantauan tahap glukosa dalam darah dalam pengurusan penyakit diabetes, dan juga dalam penjagaan kualiti makanan, contohnya, pengesanan madu tiruan. Kaedah terkini melibatkan teknik invasif, peralatan yang mahal dan juga ahli kakitangan yang terlatih untuk menjalankan ujian. Hal ini boleh menghadkan aplikasi pengesanan glukosa pada tempat kajian. Kajian ini bertujuan untuk mengaplikasikan instrumentasi biofotonik berasaskan telefon pintar untuk mengukur kepekatan glukosa menggunakan kaedah fotometrik. Peranti fotonik yang direka bentuk terdiri daripada diod pemancar cahaya inframerah dekat (NIR LED) 940 nm sebagai pemancar, fotodiod BPW34 sebagai alat pengesan, papan mikropengawal Raspberry Pi Pico yang bertindak sebagai perantara digital untuk menukarkan data yang diterima kepada voltan keluaran, dan beserta aplikasi Android iaitu Scopy sebagai osiloskop digital untuk memaparkan nilai voltan yang dikesan. Instrumen yang direka bentuk dapat mengesan glukosa pada kepekatan berbeza. Julat kepekatan glukosa iaitu 10 – 100 g/dL untuk menunjukkan tahap glukosa dalam makanan tiruan seperti madu. Penemuan kajian menunjukkan bahawa kepekatan glukosa yang lebih tinggi menghasilkan nilai voltan keluaran yang lebih tinggi. Analisis regresi linear yang diperolehi ialah $R^2 = 0.4038$ dengan nilai kecerunan -0.0019 untuk penembusan cahaya, dan $R^2 = 0.4504$ dengan nilai kecerunan 0.0011 untuk penyerapan cahaya.

NEAR-INFRARED GLUCOSE SENSING IN ADULTERATED HONEY USING SMARTPHONE-BASED PHOTOMETRIC DETECTION: A FEASIBILITY STUDY

Abstract

Glucose sensing is vital in health such as monitoring glucose levels in managing diabetes and food quality, for instance, adulterated honey detection. Current methods involve invasive, expensive equipment and highly trained personnel to carry out the test, which can limit the detection and application of glucose at on-site determination. This study aimed to apply smartphone-based biophotonic instrumentation for measuring glucose concentrations using the photometric method. The photonic device constructed consists of a 940 nm near-infrared light-emitting diode (NIR LED) as an emitter, a BPW34 photodiode as a detector, a Raspberry Pi Pico microcontroller board acts as a digital interface to convert the receiving data into output voltage, and an Android app; Scopy as a digital oscilloscope to display the output voltage value on a smartphone. The instrument detected the glucose at different concentrations. A lower and higher range of glucose concentrations was tested which is 10 – 100 g/dL for glucose in adulterated honey. The findings indicated that higher glucose concentrations resulted in higher detector output voltages. The linear regression analysis obtained is $R^2 = 0.4038$ with slope value of -0.0019 for phototransmittance and $R^2 = 0.4504$ with slope value of 0.0011 for photo absorbance

Chapter 1

Introduction

1.1 Background Study

1.1.1 Glucose and Its Compilation

Glucose is a monosaccharide and the principal source of energy for the body. It occurs naturally in foods such as fruits, honey, and carbohydrates and is critical for brain function and cell metabolism. The body metabolizes glucose to generate energy via mechanisms such as glycolysis and the citric acid cycle, and it is taken up by cells via glucose transporters, with insulin playing a key role in this process. Normal glucose is strictly maintained between 70–99 mg/dL. When it becomes too high (hyperglycaemia) or too low (hypoglycaemia), it can result in drastic health consequences, most especially for individuals with diabetes. The two primary hormones that work to control the level of glucose are insulin and glucagon.

Abnormal glucose levels can cause both acute (short-term) and chronic (long-term) complications. Acute ones include Diabetic Ketoacidosis (DKA), in type 1 diabetes, with nausea, dehydration, and coma, and Hyperosmolar Hyperglycaemic State (HHS), usually in type 2 diabetes, with profound dehydration and confusion. Hypoglycaemia (severe low sugar) can result in seizures or unconsciousness. Chronic hyperglycemia is damaging to organs and blood vessels and results in complications such as heart disease, kidney failure, nerve damage, blindness, infection, and even cognitive dysfunction. All these result from deleterious mechanisms such as oxidative stress, inflammation, and glucose attachment to proteins of the body. Both hyperglycemia and hypoglycemia, when not under control, are extremely dangerous to health.

1.1.2 NIR Spectroscopy: An Optical Method in Glucose Sensing

Near-Infrared (NIR) spectroscopy is an optical method that employs light in the 700–2500 nm range to identify and quantify chemicals such as glucose in a fast, non-invasive, and non-destructive manner. It does so by measuring the interaction of NIR light with molecules—more specifically bonds such as C-H and O-H found in glucose—to generate characteristic absorption patterns. The technique finds application in medical diagnostics, food analysis, and biotechnology. For example, in diabetic management, NIR is used to forecast the glucose level in food. In the food industry, it helps in quality or adulteration detection of the glucose content of foods like honey. NIR is quick, reagent-free, and can examine multiple substances at one time, thereby finding utility in real-time monitoring in various settings.

For all its benefits, NIR spectroscopy is not without limitation. Glucose likewise gives weak signals in the NIR and may be obscured by other components such as water or proteins, particularly in biological tissue. The method also needs sophisticated calibration models and may be susceptible to variables such as skin type or hydration when used in non-invasive testing. Emerging technologies are starting to surmount these difficulties, though. Machine learning advancements, miniaturized devices, nanotechnology, and hybrid systems are enhancing accuracy, sensitivity, and portability. Emerging innovations are trying to render NIR-based glucose sensing more accurate, cost-effective, and appropriate for daily medical applications, thereby transforming diabetes monitoring, food analysis, and industrial process control.

1.1.3 Adulterated Honey

Honey is a natural product produced by bees from flower nectar, valued for its medicinal as well as its nutritional value. Honey is made up mainly of sugars like glucose and fructose, water, enzymes, and minute amounts of vitamins and minerals. Due to its worth, honey is frequently adulterated with the inclusion of inexpensive sweeteners like glucose syrup, HFCS (high-fructose corn syrup), or sugar solutions. The practices reduce the quality and genuineness of honey and pose risks to the consumers and issues to the producers and the regulators.

Adulteration methods include the direct addition of syrups to honey, the feeding of bee's sugar rather than nectar, or the inclusion of artificial ingredients that simulate natural honey attributes. Not only do these methods deceive consumers, but they can also introduce toxic residues, compromise nutritional content, and destabilize the natural balance of sugars in honey. One of the key markers of adulteration is the ratio of glucose to fructose, which changes when other sugars are employed, especially since glucose impacts the speed at which honey crystallizes.

The implications of adulterated honey are numerous. It is toxic to consumer health, especially diabetics or additive-sensitive consumers. It is also economically injurious to small-scale, legitimate beekeepers through depressed market prices and lost credibility. Environmentally, it dampens environmentally sound beekeeping practices that encourage diversity. Regulatorially, current detection methods like HPLC or isotope analysis are accurate but expensive, time-consuming, and not easily accessible in most parts of the world.

New detection techniques are also being researched to overcome these issues. Smartphone-based biophotonics and Near-Infrared (NIR) spectroscopy enable quicker, non-destructive, and potentially inexpensive methods of glucose concentration and other markers of adulteration detection. Encouraging as they are, the techniques are still limited by sensitivity, accuracy, and calibration needs, especially for honey from diverse floral or geographical sources.

It is important to comprehend honey adulteration for the protection of consumers, honest producers, and food safety. Quick and low-cost detection tools can be made to improve honey quality control, build market confidence, and support sustainable beekeeping. Continuous innovation in areas like NIR sensing and mobile phone diagnostics has the potential to transform the way honey authenticity is tested around the world.

1.1.4 Application Of Smartphone in Biophotonic

Bio photonics is a discipline that merges light technology (photonics) and biology for analysing and comprehending living systems. It includes techniques such as spectroscopy, imaging, and optical sensing that find uses in healthcare, environmental sensing, and food safety, among others. Smartphones have emerged as handy tools in biophotonics in the recent past because of the presence of inbuilt cameras, light sources, processing, and internet connectivity. These features enable smartphones to conduct several tests and analysis in the lab, clinic, or even outdoors.

In phone-based biophotonic, the camera and flash of the phone can be utilized to detect any change in a biological sample. The light is incident on the sample, and the camera records the outcome—either a change in color or intensity of light. Dedicated apps or additional accessories such as lenses and filters are utilized to enhance the precision of such assays. It can assist techniques like absorbance, fluorescence, and even basic microscopy.

Smartphone-based devices have many benefits. They are portable, low-cost, and easy to use, making them ideal for remote or low-resource areas. Their connectivity allows results to be sent quickly to researchers or physicians. There is still, however, some challenges. Professional laboratory equipment is more sensitive than the cameras on smartphones, and variation between phone models can affect accuracy. Despite this, research and developments in software and hardware are ongoing to enhance the performance of these devices.

1.2 Problem Statement

Honey is a natural sweetener with health and financial advantages. However, it is typically adulterated with cheap sweeteners like glucose syrup, high-fructose corn syrup, or molasses. This is profitable but reduces the purity, quality, and safety of honey, which is a matter of concern to consumers, producers, and regulators. Adulterated honey tricks consumers who buy a pure and natural sweetener. It can contain unnatural sugar, as well as poisonous chemicals such as antibiotics or chemicals, that are hazardous to health—especially for those who have allergies or diabetes. This affects not only public health but also causes consumer distrust. To legitimate honey producers, especially small bees, the spurious honey is unfair competition since it drives down prices.

This nibbles at revenue, discourages honest production, and undermines the sustainability of the beekeeping industry. Detection of honey adulteration is also challenging. Current methods like high-performance liquid chromatography (HPLC) are accurate but expensive and time-consuming, which makes them not viable for application across most regions on the planet. Lack of quick, cheap, and accurate testing technologies hinders effective quality control and enforcement. Finally, adulteration impacts the environment and poses ethical concerns. It discourages sustainable beekeeping, which is required for pollination and diversity, and promotes dishonest business practice in the food industry. Therefore, there exists a need for basic, simple, and creative solutions to determine adulteration in honey, safeguard consumers, and encourage honest producers.

1.3 Objectives

General Objectives

The aim of this study is to analyse the feasibility of applying smartphone-based photometric system for near-infrared glucose sensing in adulterated honey.

1.3.1 Specific Objectives

1. To construct smartphone-based photometric detection system.
2. To prepare adulterated honey samples—three types of honey which are added with different glucose concentrations.
3. To measure output voltage and calculate absorbance and transmittance based on Beer-Lamber law.
4. To analyse stability, sensitivity and applicability of the photometric detection system for near-infrared glucose sensing in different types of honey medium

1.4 Significance of Study

The research is important in the interests of consumer health, honest producers, and food quality. By using modern, low-cost methods like NIR spectroscopy and smartphone-based sensing, the study makes it possible to detect fake honey in a quick and accurate way without needing expensive laboratory equipment. It helps protect consumers from harmful additives, makes it easier for beekeepers to authenticate their products, and promotes fair market competition. The study also enables food safety regulators to enact regulations and encourages sustainable beekeeping, hence benefiting the environment. Overall, this research fosters healthier food, more equitable trade, and better technology for detecting food fraud worldwide.

Chapter 2

Literature Review

2.1 Glucose

2.1.1 Physical properties of glucose

Glucose's physical characteristics as a solid and solution are of great relevance to food science and analytical sensing.

Its high water solubility ($\approx 900 \text{ g L}^{-1}$ at 25°C) is why honey and syrup products dissolve easily, but solubility drops sharply as solvents depolarize or decrease—the science that drives extraction, purification, and "green-chemistry" processing. Since glucose is readily precipitated when concentrated, especially where its concentration in honey is greater than about one-third, it dictates texture and shelf-life: β -glucose nucleates faster than α , and temperatures $10\text{--}20^\circ\text{C}$ accelerate granulation.

The sugar is also optically active rotating plane-polarized light $+52.7^\circ$ and this characteristic is utilized in polarimeters, NIR spectrometers, and even smartphone sensors for fast, non-destructive glucose analysis in foods and bodily fluids. Thermal analysis indicates that it melts close to 146°C (anhydrous) but decomposes above about 150°C , where caramelization and Maillard browning occur; its amorphous form melts at $\approx 31^\circ\text{C}$, information critical to the design of stable candies, tablets, and high-temperature sensors.

Also noteworthy are its solubility characteristics: glucose is moderately hygroscopic, gaining considerable mass at normal humidities, and solutions in water exhibit strongly rising viscosity ($1\text{--}10 \text{ mPa} \cdot \text{s}$ for $10\text{--}50\%$ w/v at 25°C). These characteristics govern handling, pumping, and optical pathlength adjustment in spectroscopic instruments. As dissolved glucose also raises the refractive index of a fluid in a quasi-linear fashion ($\approx 1.33 \rightarrow 1.45$ for $0\text{--}50\%$

w/v), refractometry hence becomes a simple honey authenticity test. The combination of these interlinked properties solubility, crystallization, optical rotation, heat properties, hygroscopic, viscosity, and refractive index is a rich set of tools to control food texture, preserve product integrity, and facilitate new handheld sensors to identify adulteration or monitor glucose non-invasively.

2.1.2 Glucose in honey

Glucose comprises most of the honey content, typically 25% to 40% by weight, and its concentration is commensurate with floral source, region, and processing habits. Its ratio to fructose (typically 0.9–1.4) determines the texture and predisposition to crystallization of honey, and higher glucose content enables faster granulation. Glucose is therefore an excellent marker in quality control and authenticity testing. Experiments have proven that elevated glucose levels above 38–40% on a regular basis confirm adulteration with glucose syrups or HFCS, and detection of such deviations is vital for honey purity as well as consumer confidence.

For analysis of glucose, several analytical techniques have been explored. High-performance liquid chromatography (HPLC) yields accurate results but requires laboratory facilities. In parallel, field-deployable and rapid analyses like near-infrared (NIR) spectroscopy, smartphone biophotonics, and enzymatic assay are gaining popularity. These devices, especially with the aid of machine learning, allow small-scale producers and examiners to detect adulteration accurately and at low cost. However, problems like matrix interference, access to sophisticated adulterants, and calibration remaining a prerequisite continue to impact reliability in detection. Ongoing innovation, like smartphone NIR attachments and hybrid sensing systems, continues to propel the accuracy and ease of glucose analysis in honey.

2.1.3 Glucose in food

Glucose is a naturally occurring sugar found in honey, fruit, and starch foods and commonly added to processed foods as glucose syrup or high-fructose corn syrup (HFCS). Glucose is the source of sweetness, browning (via Maillard reactions), and texture in foods. Glucose levels have been found between 2–5% in fruit juices and more than 40% in honey, and higher levels are generally indicative of adulteration. Glucose content also affects the glycemic response of foods and is hence of concern to nutritional labelling and the development of low-GI foods.

Glucose is also frequently involved in food adulteration, particularly in honey and juice, where it is adulterated for bulk or to simulate natural sweetness. Sophisticated technologies like HPLC, NIR spectroscopy, smartphone sensors, and enzyme tests are used in the analysis of glucose and detecting adulteration. While laboratory-based methods are highly sensitive, newer low-cost, portable instruments are gaining popularity for real-time field-based screening. However, measurement reliability is still affected by issues such as interference from highly complex food matrices, the presence of advanced adulterants, and calibration requirements.

Technological advances such as the application of machine learning, NIR portables with attachments, hybrid spectroscopy (e.g., Raman + NIR), and nanomaterial-supported sensors are greatly enhancing glucose detection in food. These technologies are making it easier for small-scale manufacturers, regulators, and scientists to track glucose more effectively, which is leading to food quality control, consumer protection, and fraud reduction.

2.2 Biophotonics

2.2.1 Definition

Biophotonics has typically been defined as the use of light-based tools to probe, image, or manipulate biological systems. Early definitions (e.g., Popp 2020) framed it largely as a laboratory discipline for high-resolution medical imaging and spectroscopy. The range has expanded because: more recent authors (Zhang & Chan 2021; Smith et al. 2023) include non-medical uses such as food authenticity testing and environmental monitoring, while others (Lee & Park 2024; Kumar et al. 2025) cover portable, smartphone-based platforms that bring optical diagnostics to the point-of-care and the field. Today, definitions usually highlight four pillars: different light sources (LEDs, lasers, broadband NIR/UV), sensitive cameras and detectors, a collection of techniques (NIR and Raman spectroscopy, fluorescence, OCT), and robust computational methods (machine learning, chemometrics) that transform raw light signals into valuable information.

This expanded mandate has been the source of a rich variety of applications. In medicine, biophotonics enables non-invasive glucose monitoring, and real-time honey analysis. In food science, the same optical principles quantify sugars and detect adulteration, the presence of excess glucose syrup in honey. Environmental applications range from water pollutant monitoring to assessing microbial activity. Therapeutically, light-activated treatments like photodynamic therapy remain a mainstay. Current research emphasizes interdisciplinary convergence with nanotechnology, AI, and IoT, with the dream of rapid, high-throughput, and yet inexpensive diagnostics that run on a smartphone as easily as in a hospital lab.

Despite its promise, an agreed-upon definition is not readily forthcoming. The field straddles medicine, agriculture, and industry, each with its own traditions and regulatory

constraints. Abrupt boom in handheld optics blurs lines between professional instruments and consumer devices, confusing terminology and verification requirements. As biophotonics continues to democratize and scientists strive for sustainability and accessibility definitions in the future will place greater focus on not just what equipment is used, but how far and ethically it can be applied to solve real issues.

2.2.2 Photonic devices

2.2.2(a) Emitter

Standard light-emitting diodes (LEDs) and lasers to more recent materials like quantum dots (QDs), upconversion nanoparticles (UCNPs), and organic LEDs (OLEDs). The selection of emitter is based on a range of factors, including the wavelength range needed (e.g., near-infrared (NIR) for glucose sensing), intensity, coherence, size, and cost. LEDs and diode lasers remain the Biophotonic device emitters are the source light for interrogating the biological sample, from most common due to their low price, spectral bandwidth (UV to NIR), and durability. For higher-specialized applications, QDs and UCNPs have narrow spectral bands of emission and more tissue penetration, which are suitable for high-sensitivity fluorescence detection and non-invasive sensing.

Recent advances relate to integrating these emitters into wearable and handheld devices. For instance, biophotonic smartphone sensors already utilize integrated LED flashes and optical filters to detect glucose in honey, whereas wearable health patches utilize flexible OLED arrays for real-time monitoring. Studies conducted by Zhang et al. (2021) and Kumar et al. (2024) demonstrate the role of UCNPs and diode lasers in detecting glucose in biological and food samples with detection limits as low as 0.05 mmol/L. At the same time, 3D-printed optical accessories and micro-LEDs minimize power usage while increasing portability, which makes these devices suitable for point-of-care or field testing.

In general, the advancement of emitter technology has predominantly improved performance, accessibility, and versatility in applications for biophotonic purposes. With miniaturization, cost-effectiveness, and energy savings in progress, applications of such devices are expanding beyond food authentication, medical diagnostics, and environmental

monitoring. While challenges persist such as maintaining consistency between devices and mitigating matrix interference the future tends more toward multispectral emitters, energy efficiency, and integration with AI for real-time analysis.

2.2.2(b) Detector

Detectors are the "eyes" of a biophotonic system, taking weak light flashes and transducing them into electrical signals which can be digitized and calculated. Old favorites are CCDs and InGaAs photodiodes, famous for sensing across the near-infrared (900–2500 nm) where glucose is strongly absorbing; these still dominate lab equipment like OCT scanners and benchtop NIR spectrometers. For portable or consumer-grade instruments, however, low-cost CMOS sensors already found in smartphones are the first option, providing microsecond read-out rates and broad spectral coverage (UV-visible-NIR) in an economical package. Concurrently, frontier research is pushing sensitivity downwards and increasingly broad bandwidth: graphene photodetectors take responsivity into the mid-IR; quantum-dot-enhanced CMOS chips and single-photon avalanche diodes (SPADs) can detect single photons, enabling trace-level glucose or biomarker analysis; and hybrid nanomaterial stacks deposit fluorescence or Raman signals directly on silicon for single-shot multiplex analysis.

Performance trade-offs focus on spectral range, noise, speed, and cost. InGaAs diodes handle NIR glucose bands well (1600 nm, 2100 nm) but add to device expense; CCDs offer high pixel counts but lower frame rates, suitable for laboratory imaging applications than real-time field use; CMOS cameras are inexpensive and fast but less light-sensitive in limiting conditions. Nanomaterial detectors narrow this gap somewhat but are still costly to manufacture. Despite this, there are quite a few convenient demonstrations: phone cameras with test strips quantify glucose in fruit juices in the field; SPAD-based wearables quantify interstitial-fluid glucose to clinical-quality levels; and NIR photodiode arrays coupled with portable spectrometers verify honey by identifying glucose syrup adulteration at >40 % w/w.

As detector technology shrinks and becomes more sensitive, biophotonic devices are moving out of specialized labs and onto farms, factories, clinics, and even wearable wrist patches. Future challenges are to make calibration among different sensor types of routine, prevent matrix interference from protein or acid in real samples, and decrease the cost of manufacturing graphene and quantum-dot architectures. With the resolution of these challenges, ubiquitous real-time optical analytics will be possible for food safety, medical diagnostics, and environmental monitoring.

2.2.2(c) Manipulator/modulator

Modulators are also critical in biophotonic devices in the sense that they control the characteristics of light, be it wavelength, intensity, phase, or polarization. These elements enhance the purity and fidelity of signals, particularly critical for applications such as glucose sensing where optical signals are weak and may be buried within complex biological or food matrices. Straightforward modulators like optical filters are ubiquitous since they are both cheap and easy to work with, allowing fixed or narrowband wavelength selection—ideal for isolating glucose's NIR absorption bands at 1600 nm and 2100 nm. Faster or even tunable modulators are used in more complex systems, however, such as acousto-optic modulators (AOMs), spatial light modulators (SLMs), and newer graphene-based electro-optic modulators (EOMs) that facilitate better control of the light for more sophisticated analyses.

This variability is expressed in recent progress. AOMs have been used in Raman spectroscopy instruments for accurate laser intensity control in food material glucose analysis, while SLMs (such as liquid crystal on silicon technology) are used in OCT and holography for phase and amplitude modulation of light in the acquisition of high-resolution images. Graphene and plasmonic modulators are the cutting edge with ultrafast modulation rates (up to GHz) and continuously variable spectral control, both of which are essential for real-time, wearable, or multiplex glucose sensing. Graphene EOMs, for example, have been integrated into flexible biosensors for non-invasive glucose monitoring, and plasmonic metamaterials to enhance contrast in fluorescence-based glucose assays.

Modulators are also being redesigned for handheld and field-oriented biophotonic devices. Smartphone glucose analysis platforms now feature tiny optical filters and tunable components to manage wavelength specificity, which are accurate even in uncontrolled environments. With advancing biophotonic technology, especially in wearable diagnostics and food authentication, modulators will continue to advance in speed, miniaturization, and spectral

control ultimately resulting in highly sensitive, selective, and affordable glucose monitoring devices in medical, food, and environmental contexts.

2.2.3 Optical methods

2.2.3(a) Photometric

Photometric methods are the foundation in biophotonic glucose sensing due to variations in light intensity resulting from absorption, emission, or scattering by a sample. Absorbance photometry measures the loss of light upon passing through a glucose-containing medium, which is most apt in UV-visible and near-infrared (NIR) spectral regions where glucose exhibits absorption bands at wavelengths of 1600 nm and 2100 nm. Fluorescence photometry, on the other hand, quantitates light emitted by intrinsic or enzyme-labeled fluorophores upon excitation and offers high sensitivity for glucose detection. Photometry based on scattering measures changes in the scattered light to infer information on turbid or multi-component samples, such as dairy or fruit juices.

Photometric devices that are biophotonic cover laboratory-based spectrophotometers along a continuum to small, handheld, and smartphone-enabled devices. At the lab, high-accuracy instruments with photomultiplier tubes or InGaAs detectors are used to quantify glucose from samples like honey. Field portability is attained through portable instruments, such as LED-based NIR spectrometers or handheld scattering photometers, while having acceptable sensitivity. Smartphone platforms are becoming widespread options of convenience and affordability, using intrinsic cameras or extrinsic attachments for performing absorbance or fluorescence photometry with colorimetric test strips or CMOS sensors.

These photometric tools find many uses. In food science, NIR and absorbance photometry have been utilized to detect adulteration of glucose in honey and quantify sugar content in juices. In diagnostics, photometry based on fluorescence enables non-invasive glucose monitoring with high sensitivity, and absorbance methods enable wearable, continuous monitoring. Photometry based on scattering is also used in dairy and environmental

monitoring, expanding glucose detection to more complex matrices. As a result of constant developments in miniaturization, sensitivity of sensors, and integration into mobile technology, photometric biophotonic systems are also becoming highly multidisciplinary tools of glucose measurement in health care, food, and environmental practice.

2.2.3(b) Spectrometric

Spectrometric methods are essential in biophotonic glucose sensing since they can potentially provide comprehensive molecular information through light-analyte interaction across a variety of spectrums. Among all the basic methods, Near-Infrared (NIR) spectroscopy is most widely used due to its ability to detect overtone and combination molecular vibrations' bands—particularly C-H and O-H bond vibrations found in glucose—between 700–2500 nm. Raman spectroscopy is highly molecularly specific by measuring inelastic scattering of monochromatic light, providing a fingerprint of glucose even with complicated mixtures. Fourier-Transform Infrared (FTIR) spectroscopy scans the mid-infrared part of the spectrum (2500–25,000 nm), where precise molecular characterization occurs, but it is generally limited to controlled laboratory settings due to the complexity of the instruments.

The spectrometric techniques are utilized in a range of biophotonic devices. Laboratory systems based on benchtop NIR and FTIR spectrometers with InGaAs and MCT detectors are sensitive enough to quantify glucose in food products like honey and biological fluids. Raman systems that use diode lasers and CCD detectors also enable high-resolution detection of glucose, particularly in non-invasive diagnostics. Portable versions of such devices are now available, such as handheld NIR and Raman spectrometers using LEDs or compact laser systems and CMOS detectors, enabling field-based glucose analysis. Smartphone platforms further increase accessibility, using miniaturized NIR and Raman modules for on-line glucose sensing in food and medical applications.

Applications of spectrometric biophotonics range widely. NIR and Raman spectroscopy have been used successfully in food analysis to detect glucose adulteration in honey and quantify sugar in fruit juices with accuracies greater than 90%. FTIR spectroscopy has been useful in dairy and processed food analysis in the quantification of low levels of glucose with

minimal sample preparation. In clinical diagnostics, non-invasive NIR and wearable Raman sensors showed superior correlation ($\geq 91\%$) with laboratory glucometers, offering promising substitutes for the management of diabetes. Moreover, spectrometric methods enable the detection of pathogens and environment monitoring, wherein molecular specificity and high sensitivity enable the determination of glucose in fermentation, water, and other matrix-rich systems. Such accomplishment validates spectrometric biophotonics as a successful tool set for holistic, non-destructive glucose analysis across various industries.

2.2.3(c) Colorimetric

Colorimetric methods are at the center of biophotonics because they are simple, inexpensive, and very effective for the detection of analytes like glucose. Colorimetric methods rely on visible color changes from selective reactions, typically in the 400–700 nm range. The most common approach employs enzymatic reactions—i.e., the glucose oxidase-peroxidase (GOD-POD) system—with colored products proportional to glucose concentration. These color changes are quantified in terms of reflectance or absorbance, with detection ranging from photodiodes to smartphone CMOS cameras. This optical character makes colorimetry highly suitable for on-site, real-time glucose analysis in food, clinical, and environmental uses.

The instrumentation for colorimetric biophotonics ranges from traditional laboratory-based setups to highly portable and smartphone-integrated platforms. CCD or photodiode detector-based benchtop colorimeters offer high-precision measurements, as demonstrated for glucose analysis in honey and clinical samples. Handheld colorimetric devices, based on LEDs and small sensors, offer the potential for field analysis of foods such as juices and dairy products. More recent developments have transferred these capabilities to smartphones through the use of 3D-printed light guides and test strips, enabling quantitative glucose analysis via camera-based absorbance sensing. They provide low-cost, practical solutions for non-specialist end-users in both the developed and resource-limited environments.

The uses of colorimetric biophotonic systems are numerous. They are used in food quality control to detect glucose adulteration of honey and to quantify sugar concentration in fruit juices and dairy products, where the limits of detection are typically between 0.1 and 0.5 g/100 g. These broad applications, combined with simplicity and low cost, place colorimetric biophotonic methods at the center of low-cost glucose sensing.