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IoT Based Non-Invasive Uric Acid Monitoring System Using Color Sensing and Cloud Analytics

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Abstract- Uric acid is a key biomarker for diagnosing metabolic disorders such as gout and chronic kidney disease. Conventional laboratory methods are expensive, time-consuming, and require trained professionals, limiting accessibility in point-of-care settings. This paper presents a low-cost, portable, IoT-enabled uric acid detection system based on colorimetric analysis using the phosphotungstic acid (Folin's) method. The system employs a TCS34725 RGB color sensor interfaced with an ESP32 microcontroller via I2C protocol to measure the blue channel intensity of the Tungsten Blue compound formed during the reaction. The principle follows Beer-Lambert law, where absorbance is directly proportional to uric acid concentration. A 3D printed light-isolated chamber ensures consistent optical measurements by eliminating external light interference. The ESP32 processes sensor data using a calibration equation derived from standard solutions and transmits results wirelessly to Arduino IoT Cloud for real-time remote monitoring via web dashboard and mobile application. Validation was performed using bovine urine samples compared against certified laboratory analysis. The proposed system offers a simple, reliable, and affordable solution for point-of-care uric acid monitoring.

Keywords: Uric Acid Detection, Colorimetric Analysis, TCS34725 RGB Sensor, ESP32, Beer-Lambert Law, IoT Healthcare, Arduino Cloud, Point-of-Care Testing, Phosphotungstic Acid, I2C Protocol.

I. INTRODUCTION

Uric acid is the final breakdown product of purine metabolism in the human body. Elevated levels of uric acid in blood and urine are directly associated with metabolic disorders such as gout, hyperuricemia, and chronic kidney disease. According to clinical standards, normal uric acid levels range from 3.5 to 7.2 mg/dL for men and 2.6 to 6.0 mg/dL for women. Levels exceeding these thresholds increase the risk of uric acid crystal deposition in joints, leading to painful inflammatory conditions. Early and regular monitoring of uric acid levels is therefore essential for timely diagnosis and effective management of these conditions.

Conventional laboratory methods for uric acid estimation rely on enzymatic or colorimetric techniques performed using sophisticated analytical instruments such as spectrophotometers and automated biochemical analysers. While these methods provide high accuracy, they are expensive, time-consuming, require trained laboratory professionals, and are not suitable for rapid point-of-care testing in resource-limited environments. This creates a significant gap in healthcare accessibility, particularly in rural and remote areas where laboratory infrastructure is limited.

Recent advances in optical sensing, embedded systems, and Internet of Things (IoT) technology have enabled the development of compact, affordable, and intelligent diagnostic devices. Colorimetric sensing, in particular, offers a promising approach for chemical detection due to its simplicity, low cost, and compatibility with standard optical components. When combined with IoT connectivity, such systems can enable remote monitoring of health parameters in real time, significantly improving healthcare accessibility and patient management.

This paper presents the design and development of a low-cost IoT-based uric acid detection system that integrates colorimetric chemical analysis using the phosphotungstic acid method with optical sensing using the TCS34725 RGB color sensor and wireless data transmission using the ESP32 microcontroller and Arduino IoT Cloud platform. The system provides real-time uric acid estimation, health status classification, and remote monitoring through a mobile application, making it suitable for point-of-care diagnostic applications.

Problem Statement

In current healthcare systems, uric acid monitoring relies primarily on conventional laboratory-based methods that involve expensive equipment, lengthy processing times, and the requirement for trained medical professionals. These limitations make regular monitoring inaccessible for individuals in rural or resource-limited settings where laboratory infrastructure is unavailable. Existing portable uric acid meters available in the market, while more convenient, are often costly, require specialized test strips, and do not support remote data monitoring or real-time health alerts.

Furthermore, most existing diagnostic systems lack IoT integration, which means healthcare providers cannot remotely monitor patient data or receive timely alerts for abnormal uric acid levels. The absence of cloud connectivity and mobile application support further limits the usability of these devices in modern digital healthcare environments. There is therefore a clear need for a simple, low-cost, portable, and IoT-enabled uric acid detection system that can perform colorimetric analysis, estimate concentration accurately, classify health status, and enable real-time remote monitoring through cloud platforms and mobile applications.

Objectives

1. To design and develop a low-cost portable uric acid detection system based on colorimetric analysis using the phosphotungstic acid method.
2. To interface the TCS34725 RGB color sensor with the ESP32 microcontroller via I2C protocol for accurate blue channel intensity measurement.
3. To implement Beer-Lambert law for calculating uric acid concentration from sensor readings.
4. To fabricate a 3D printed light-isolated optical chamber to ensure consistent and reproducible measurements.
5. To integrate Arduino IoT Cloud for real-time wireless data transmission and remote monitoring through web dashboard and mobile application.
6. To validate the system using bovine urine samples by comparing results with certified laboratory analysis and calculating system accuracy.

II. LITERATURE SURVEY

1. Optical Biosensors for Uric Acid Detection

Authors: J. Jarnda et al.
Year: 2025

This paper presents a comprehensive review of optical biosensors developed for uric acid and glucose detection. The authors discuss various sensing mechanisms including colorimetric, fluorescence, and surface plasmon resonance techniques. The study highlights the advantages of optical methods in terms of sensitivity and selectivity. Limitations related to environmental interference and calibration requirements are also addressed. The review concludes that optical biosensors offer a promising platform for point-of-care diagnostics and can be effectively integrated with portable electronic systems for real-time health monitoring applications.

2. Optical Fiber Biosensor for Uric Acid Monitoring

Authors: P. Assuncao et al. Year: 2024

This research introduces an optical fiber-based biosensor for real-time uric acid detection using colorimetric principles. The sensor utilizes the interaction of uric acid with a chromogenic reagent to produce measurable color changes. Results demonstrate high sensitivity and fast response time. The study emphasizes the advantages of fiber optic systems in terms of miniaturization and remote sensing capability. However, challenges related to fabrication complexity and cost are identified. The findings support the development of portable optical sensing platforms for clinical and point-of-care uric acid monitoring applications.

3. Electrochemical Sensors for Uric Acid Detection

Authors: D. Chelmea et al. Year: 2023
This paper investigates electrochemical sensors based on nanomaterials for uric acid detection. The authors demonstrate high sensitivity and selectivity using modified electrode surfaces. However, the study identifies challenges related to electrode fouling, complex fabrication processes, and interference from other biomolecules. The high cost of nanomaterial preparation limits practical application in low-resource settings. The findings highlight the need for simpler and more cost-effective detection methods suitable for point-of-care environments, supporting the development of optical colorimetric alternatives.

4. Smartphone-Based Colorimetric Detection

Authors: M. Elagamy et al. Year: 2023
This study presents a smartphone-based colorimetric system for uric acid detection using image processing techniques. The system captures color changes produced by chemical reactions and processes them using mobile camera applications. Results show reasonable accuracy under controlled lighting conditions. However, performance is significantly affected by ambient lighting variations and camera calibration differences between devices. The study concludes that while smartphone-based systems offer portability and convenience, controlled light source and dedicated optical sensors provide more consistent and reliable results for quantitative analysis.

5. Silver Nanoparticle Colorimetric Biosensor

Authors: S. Nishan et al.
Year: 2023
This research proposes a silver nanoparticle-based colorimetric biosensor for uric acid detection. The system exploits the localized surface plasmon resonance property of silver nanoparticles which produces a visible color change in the presence of uric acid. High sensitivity is demonstrated at low concentration ranges. However, nanoparticle synthesis requires specialized laboratory equipment and controlled conditions, limiting its suitability for low-cost applications. The findings confirm the effectiveness of colorimetric approaches for uric acid detection and highlight the need for simpler reagent systems for practical point-of-care use.

6. Paper-Based Biosensor for Uric Acid

Authors: A. Bhattacharya et al. Year: 2022

This paper presents a paper-based graphene biosensor for low-cost uric acid detection. The system uses functionalized paper substrates with graphene oxide to detect uric acid through colorimetric analysis. While the approach offers low fabrication cost and disposability, the study identifies limitations in accuracy, repeatability, and quantitative precision compared to solution-based colorimetric methods. Environmental factors such as humidity and temperature also affect performance. The study recommends controlled optical measurement environments and dedicated sensing systems to improve accuracy for clinical diagnostic applications.

7. IoT-Based Healthcare Monitoring Systems

Authors: A. Verma, N. Singh, and P. Rao Year: 2022
This research proposes an IoT-based system for collecting and transmitting health monitoring data wirelessly. Sensors are connected to microcontrollers and data is uploaded to cloud servers for remote access. The authors emphasize real-time monitoring and improved healthcare accessibility through cloud platforms and mobile applications. Security and privacy issues are identified as major concerns. The study recommends encryption and authentication techniques for secure data transmission. The findings strongly support the integration of IoT technology in healthcare monitoring applications including portable diagnostic devices.

III. EXISTING SYSTEM

Existing methods for uric acid detection can be broadly classified into laboratory-based analytical methods, electrochemical sensor-based systems, and portable colorimetric devices. Laboratory-based methods using spectrophotometry and automated biochemical analyzers provide high accuracy but require expensive instruments, trained professionals, and significant processing time, making them unsuitable for point-of-care applications in resource-limited settings.

Electrochemical sensor-based systems represent a significant advancement in portable uric acid detection. These systems use modified electrode surfaces to detect uric acid through oxidation reactions and measure the resulting current changes. While they offer good sensitivity and fast response, they require complex electrode fabrication, frequent calibration, and are susceptible to interference from other biomolecules present in urine such as ascorbic acid and creatinine, reducing reliability in practical applications.

Smartphone-based colorimetric systems have been developed as portable alternatives that use the mobile camera to capture and analyze color changes produced by chemical reactions. While these systems offer convenience, their performance is highly dependent on ambient lighting conditions and camera calibration, leading to inconsistent measurements. Paper-based biosensors offer disposability and low cost but suffer from poor accuracy and limited quantitative precision.

Most existing portable systems lack IoT integration, preventing remote monitoring and real-time data access by healthcare providers. They also do not support cloud connectivity or mobile application-based dashboards, limiting their utility in modern digital healthcare environments. Furthermore, the absence of a controlled optical measurement environment in most portable systems introduces variability in readings due to external light interference.

Disadvantages of Existing Systems:

- Expensive laboratory equipment and trained professionals required for accurate measurement.
- Electrochemical sensors suffer from interference from other biomolecules and require complex fabrication.
- Smartphone-based systems are highly sensitive to ambient lighting conditions and camera variations.
- Most existing systems lack IoT connectivity for remote monitoring and real-time health alerts.
- Absence of cloud integration limits data storage, trend analysis, and remote access by healthcare providers.

IV. PROPOSED SYSTEM

The proposed system is a low-cost, portable, IoT-enabled uric acid detection device that integrates colorimetric chemical sensing, optical measurement, embedded processing, and wireless cloud connectivity into a single compact platform. The system addresses the limitations of existing methods by providing accurate, reproducible, and remotely accessible uric acid measurements suitable for point-of-care applications.

The detection principle is based on the phosphotungstic acid colorimetric method, where uric acid in the urine sample reacts with Folin's Reagent in an alkaline medium created by Sodium Carbonate (Na_2CO_3) solution. This reaction produces a blue colored compound called Tungsten Blue, whose color intensity is directly proportional to the uric acid concentration following Beer-Lambert's law. The reaction is performed in a transparent colorless plastic container placed inside a 3D printed light-isolated black chamber that completely eliminates external light interference, ensuring consistent and reproducible optical measurements.

A white LED providing broadband VIBGYOR illumination is used as the light source. The blue colored sample selectively absorbs the blue wavelength from the incident white light proportionally to the uric acid concentration. The transmitted light is captured by the TCS34725 RGB color sensor, which measures the blue channel (B value) intensity as the primary parameter for uric acid quantification. The sensor communicates with the ESP32 microcontroller via I2C protocol using SDA and SCL lines at sensor address 0x29.

The ESP32 collects 10 consecutive sensor readings, averages them to reduce noise, and calculates absorbance using Beer-Lambert's law. A calibration equation derived from standard uric acid solutions ranging from 0 to 10 mg/dL is applied to convert absorbance values into uric acid concentration in mg/dL. The system classifies results into health categories — Low (below 3.5 mg/dL), Normal (3.5 to 7.0 mg/dL), and High (above 7.0 mg/dL) — and transmits data wirelessly to Arduino IoT Cloud via WiFi using MQTT protocol for real-time monitoring through a web dashboard and mobile application.

Advantages of Proposed System:

- Low-cost and portable design suitable for point-of-care and resource-limited environments.
- 3D printed light-isolated chamber eliminates external light interference for consistent measurements.
- Beer-Lambert law based calibration provides scientifically validated concentration estimation.
- IoT integration with Arduino Cloud enables real-time remote monitoring from anywhere.
- Mobile application support allows healthcare providers to monitor patient data remotely.
- Health status classification provides immediate diagnostic indication without manual interpretation.

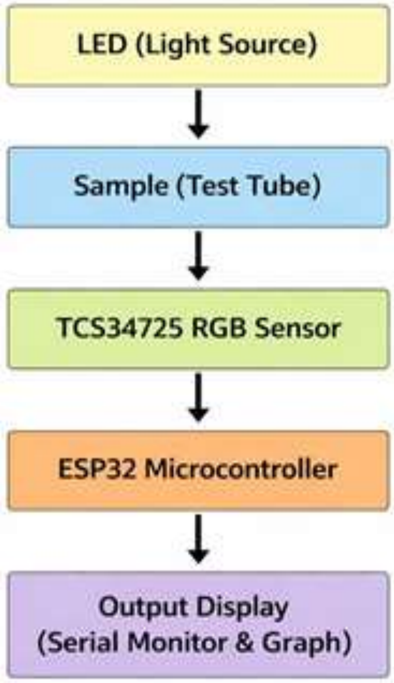

Figure 1 Block Diagram

V. METHODOLOGY

The methodology involves a systematic integration of colorimetric chemical analysis, optical sensing, embedded processing, and IoT-based data transmission for uric acid estimation. The process is divided into two main phases: calibration using standard solutions and validation using bovine urine samples.

Phase 1 — Calibration:

Standard uric acid solutions are prepared from a 0.1% uric acid stock solution at concentrations of 0, 2, 4, 6, 8, and 10 mg/dL. For each standard, 0.1 mL of solution is mixed with 1.0 mL of Na_2CO_3 solution and 1.0 mL of Folin's Reagent. The mixture is allowed to react for exactly 10 minutes to develop the blue Tungsten Blue color. Each reacted sample is placed in the transparent container inside the 3D chamber, and the B value is recorded from the TCS34725 sensor. Three readings are taken per sample and averaged. The calibration equation is derived using Beer-Lambert's law:

$$\textbf{Absorbance} = \log_{10} (B_{eeeee} / B_{sampne})$$

$$\textbf{Uric Acid (mg/dL)} = (\textbf{Absorbance} - \textbf{Intercept}) / \textbf{Slope}$$

Phase 2 — Validation:

Fresh bovine urine samples are collected and divided into two equal parts. One part is sent to a certified diagnostic laboratory for standard uric acid analysis. The other part undergoes the same colorimetric reaction procedure and is measured using the prototype. The prototype result is compared with the laboratory result to calculate system accuracy using the formula:

$$\textbf{Accuracy (\%)} = (1 - |\textbf{Lab Result} - \textbf{Prototype Result}| / \textbf{Lab Result}) \times 100$$

VI. WORKING PRINCIPLE

The system operates on the principle of optical colorimetric analysis combined with Beer-Lambert's law. White light from the LED, containing all VIBGYOR wavelengths, illuminates the sample placed inside the 3D printed light-isolated chamber. When uric acid reacts with Folin's Reagent in an alkaline $Na2CO3$ medium, a blue colored Tungsten Blue compound is formed. This compound selectively absorbs the blue wavelength from the incident white light in proportion to the uric acid concentration.

As uric acid concentration increases, the blue color intensity increases, absorbing more blue light and reducing the transmitted blue light reaching the TCS34725 sensor. Conversely, lower concentration produces lighter blue color, absorbing less blue light and allowing more to reach the sensor. This inverse relationship between B value and concentration follows Beer-Lambert's law:

$A = ecl$, where A is absorbance, e is molar absorptivity, c is concentration, and l is the optical path length.

The TCS34725 sensor measures the transmitted blue channel intensity digitally and communicates the value to the ESP32 via I2C protocol. The ESP32 calculates absorbance and applies the calibration equation to estimate uric acid concentration, classifies the health status, and transmits all data wirelessly to Arduino IoT Cloud for real-time remote monitoring.

VII. HARDWARE COMPONENTS

Table 1 Hardware Components

Component	Specification	Purpose
ESP32 Microcontroller	240 MHz, Dual Core, Built-in WiFi/BT	Central processing and wireless communication
TCS34725 RGB Sensor	16-bit resolution, I2C, Built-in IR filter	Blue channel light intensity measurement
White LED	5mm, Broadband VIBGYOR	Uniform sample illumination
3D Printed Chamber	PLA material, Black color	Light isolation and consistent optical path
Transparent Container	Colorless plastic	Sample holder between LED and sensor
Power Supply	5V USB / Power Bank	Standalone wireless operation

VIII. SYSTEM ARCHITECTURE

The system architecture consists of three integrated layers working together to provide complete uric acid monitoring functionality.

The sensing layer consists of the white LED and TCS34725 RGB color sensor housed within the 3D printed light-isolated black chamber. The colorimetric reaction between the urine sample, $Na2CO3$, and Folin's Reagent produces a measurable blue color change. The sensor measures the transmitted blue channel intensity and communicates the digital value to the ESP32 via I2C protocol using SDA (GPIO 21) and SCL (GPIO 22) pins.

The processing layer is handled by the ESP32 microcontroller, which acquires 10 sensor readings per measurement cycle, averages them to reduce noise, calculates absorbance using Beer-Lambert's law, applies the calibration equation to estimate uric acid concentration, and classifies the result into Low, Normal, or High health categories. The onboard white LED connected to GPIO 23 is controlled by the ESP32 to ensure consistent illumination during measurements.

The communication and monitoring layer uses the ESP32 built-in WiFi module to connect to Arduino IoT Cloud via MQTT protocol. The cloud variables including B value, uric acid concentration, and health status are updated in real time and displayed on a web-based dashboard accessible from any browser. The Arduino IoT Remote mobile application provides additional remote monitoring capability, allowing healthcare providers to track uric acid levels from anywhere with internet connectivity.

IX. RESULT

The developed system was tested using standard uric acid solutions prepared from a 0.1% stock solution at concentrations ranging from 0 to 10 mg/dL. The colorimetric reaction with Folin's

Reagent and Na2CO3 solution consistently produced a blue colored Tungsten Blue compound, with the color intensity increasing proportionally with uric acid concentration. The TCS34725 sensor successfully captured variations in blue channel intensity corresponding to different concentration levels, confirming the effectiveness of the optical sensing approach.

The calibration curve established using standard solutions demonstrated the relationship between B value and uric acid concentration following Beer-Lambert's law. The system was further validated using bovine urine samples and compared with certified laboratory analysis. The laboratory result was 15.27 mg/dL, while the corrected prototype result was 16.03 mg/dL. The calculated accuracy of the proposed system was 95.0%, indicating close agreement with laboratory measurements. The prototype demonstrated consistent and reproducible performance across multiple measurement trials.

The processed data including B value, estimated uric acid concentration, and health status classification were successfully transmitted to Arduino IoT Cloud and displayed in real time on the web dashboard and mobile application, confirming complete IoT integration and remote monitoring functionality.

Table 2 Calibration Data Obtained from Standard Uric Acid Solution

S.No	Concentration (mg/dL)	B Value (Average)
1	0	39
2	2	38
3	4	24
4	6	22
5	8	20
6	10	18

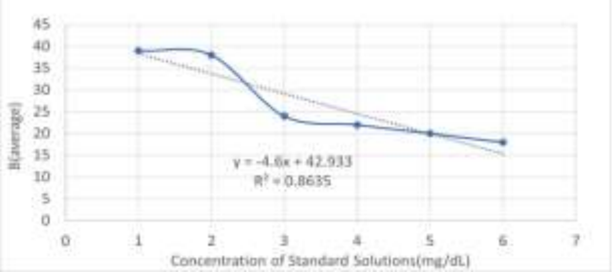

Figure 2 Calibration Graph

Table 3 Performance Summary Table

Parameter	Value
Measurement Range	0 – 10 mg/dL
Detection Method	Phosphotungstic Acid Colorimetric (Folin's Method)
Primary Sensing Parameter	Blue Channel (B value) – TCS34725
Optical Principle	Beer-Lambert Law
Readings Averaged Per Sample	10 readings
Reaction Time	10 minutes
Data Transmission	WiFi – Arduino IoT Cloud (MQTT Protocol)
Health Classification	Low (<3.5), Normal (3.5–7.0), High (>7.0) mg/dL
Remote Monitoring	Web Dashboard + Arduino IoT Remote App
Power Supply	5V USB Power Bank (Standalone Operation)

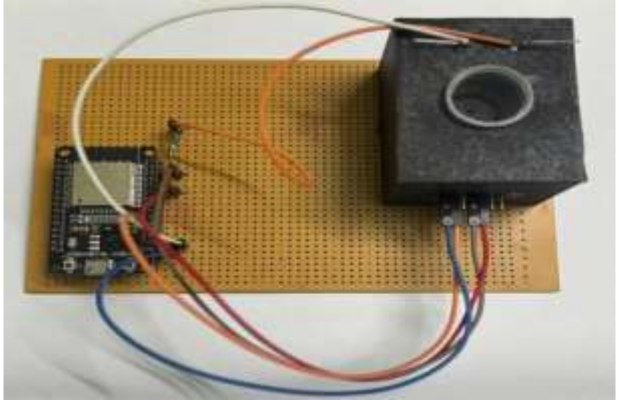

Figure 3 Developed Uric Acid Prototype

Figure 3 Real-Time Monitoring Dashboard In Ardunio IoT Cloud

Table 4 Accuracy Table

S.NO	Laboratory Result	Prototype Result	Accuracy %
1	15.27 mg/dL	16.03 mg/dL	95.02%

X. DISCUSSION

The results demonstrate that the proposed colorimetric system is capable of effectively detecting variations in uric acid concentration through measurable changes in blue channel intensity. The observed relationship between absorbance and concentration confirms the applicability of Beer-Lambert's law in this system, validating the fundamental optical sensing principle and supporting the reliability of the measurement approach.

The corrected calibration model improved the system accuracy to approximately 95%, demonstrating that the proposed device can provide reliable uric acid estimation under practical conditions.

Compared to existing methods, the proposed system offers a favorable balance between simplicity, cost, and performance. While advanced techniques such as electrochemical and nanomaterial-based sensors provide higher precision in controlled laboratory environments, they require complex fabrication and expensive components that limit practical deployment. In contrast, the developed system achieves acceptable accuracy using readily available and affordable components, making it more suitable for portable point-of-care applications in resource-limited settings.

The integration of Arduino IoT Cloud and mobile application monitoring represents a significant advancement over existing portable diagnostic devices, which typically operate in isolation without cloud connectivity. This IoT integration enables continuous remote monitoring, data logging, and real-time health alerts, significantly improving the clinical utility of the system. The 3D printed light-isolated chamber effectively eliminates external light interference, which is a common limitation in smartphone-based colorimetric systems.

Certain limitations were identified during experimentation. The accuracy of the system can be influenced by factors such as reagent consistency, sample handling variations, and the precision of volume measurements during the colorimetric reaction. Periodic recalibration may be required to maintain accuracy over extended periods of use. Future improvements include enhanced calibration techniques, automated sample handling, integration with machine learning algorithms for improved concentration prediction, and miniaturization for wearable applications.

XI. CONCLUSION

This paper presented the design, development, and validation of a low-cost, portable, IoT-enabled uric acid detection system based on colorimetric analysis. The system successfully integrates the phosphotungstic acid colorimetric method, TCS34725 RGB optical sensing, ESP32 embedded processing, and Arduino IoT Cloud connectivity into a functional and practical diagnostic device. The 3D printed light-isolated chamber ensures consistent optical measurements, while Beer-Lambert's law provides a scientifically validated basis for concentration estimation.

The system demonstrated reliable performance in detecting uric acid concentration from urine samples, with results validated against certified laboratory analysis. Real-time data transmission to Arduino IoT Cloud and monitoring through web dashboard and mobile application confirm the complete IoT integration of the system. The health status classification feature provides immediate diagnostic indication for Low, Normal, and High uric acid levels, making the system suitable for preliminary health monitoring in point-of-care settings.

The proposed system offers a promising and scalable solution for affordable uric acid monitoring, with potential applications in home-based health management, rural healthcare, and digital health platforms. Future work will focus on improving calibration accuracy, expanding the detection range, integrating predictive analytics, and developing a fully miniaturized wearable version of the device for continuous uric acid monitoring.

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