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DEVELOPMENT OF PORTABLE DIAGNOSTIC TOOLS FOR RAPID DETECTION OF METAPNEUMOVIRUS IN HUMANS

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Abstract: Human metapneumovirus (HMPV) poses a global health threat, but its detection remains challenging due to limited environmental monitoring. This study aims to develop a portable diagnostic tool for rapid HMPV detection by integrating cutting-edge biotechnology (CRISPR-Cas system and immunoassay) with air quality sensors on an Internet of Things (IoT)-based microfluidic platform controlled by an ESP32 microcontroller. The system is supported by a companion application and data analysis using Vertex AI, and is capable of providing results in less than fifteen minutes. The development results demonstrate the potential for improving detection accuracy and reliability, particularly with further development of virus-specific biosensors, sensor optimization, and algorithms. This technology is effective as a complementary tool for early screening and environment-based risk management in areas with limited laboratory facilities, although it does not completely replace molecular diagnostic methods such as PCR. A rapid diagnostic approach based on environmental sensors, IoT, and artificial intelligence is a promising strategy to improve early HMPV detection, accelerate public health responses, and strengthen respiratory infection prevention through integrated environmental monitoring and education functions.

Keywords: air quality; CRISPR-Cas; Human Metapneumovirus (HMPV); Internet of Things, portable diagnostic; public health; rapid detection; sensors.

Abstrak: Human metapneumovirus (HMPV) merupakan ancaman bagi kesehatan global, namun pendeteksiannya masih sulit akibat keterbatasan pemantauan lingkungan. Studi ini bertujuan mengembangkan alat diagnostik portabel untuk deteksi cepat HMPV melalui integrasi bioteknologi mutakhir (sistem CRISPR-Cas dan immunoassay) dengan sensor kualitas udara pada platform mikrofluida berbasis Internet of Things (IoT) yang dikendalikan mikrokontroler ESP32. Sistem ini didukung aplikasi pendamping dan analisis data menggunakan Vertex AI, serta mampu memberikan hasil dalam waktu kurang dari lima belas menit. Hasil pengembangan menunjukkan potensi peningkatan akurasi dan keandalan deteksi, terutama dengan pengembangan lanjutan berupa biosensor spesifik virus, optimalisasi sensor, dan algoritma. Teknologi ini efektif sebagai alat pelengkap untuk skrining awal dan manajemen risiko berbasis lingkungan di wilayah dengan keterbatasan fasilitas laboratorium, meskipun tidak sepenuhnya menggantikan metode diagnostik molekuler seperti PCR. Pendekatan diagnostik cepat berbasis sensor lingkungan, IoT, dan kecerdasan buatan menjadi strategi menjanjikan untuk meningkatkan deteksi dini HMPV, mempercepat respons kesehatan masyarakat, serta memperkuat pencegahan infeksi saluran pernapasan melalui fungsi pemantauan dan edukasi lingkungan yang terintegrasi.

Kata kunci: CRISPR-Cas; diagnostik portabel; deteksi cepat; Human Metapneumovirus (HMPV); kesehatan masyarakat; IoT (Internet of Things); sensor kualitas udara.

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INTRODUCTION

Human metapneumovirus (HMPV) is an emerging respiratory pathogen that has been recognized as a significant global public health concern due to its widespread prevalence and substantial disease burden among vulnerable populations, including young children, older adults, and immunocompromised individuals [1] [2] [3]. Since its identification, HMPV has been associated with a broad spectrum of respiratory illnesses ranging from mild upper respiratory tract infections to severe pneumonia and bronchiolitis, often leading to hospitalization [4] [5]. Serological studies indicate that global exposure to HMPV is extensive, with most individuals infected during early childhood, highlighting its public health relevance [6].

Despite its clinical importance, the early diagnosis of HMPV remains challenging. The clinical manifestations of HMPV infection are largely indistinguishable from those caused by other respiratory viruses, such as respiratory syncytial virus (RSV) and influenza, complicating clinical diagnosis and patient triage [7]. Currently, laboratory-based diagnostic approaches—including reverse transcription polymerase chain reaction (RT-PCR), viral culture, multiplex respiratory panels, and immunofluorescence assays—are considered reference standards for HMPV detection [8]. However, these methods require well-equipped laboratories, trained personnel, and relatively long processing times, making them impractical for routine use in resource-limited settings.

In addition to diagnostic constraints, the absence of an effective environmental monitoring system for airborne viral pathogens further exacerbates the transmission of HMPV. Environmental surveillance capable of detecting viral presence or infection risk in shared spaces could provide valuable insights into virus circulation patterns and post-infection dynamics, yet such systems are rarely available or integrated into routine public health practice. This limitation restricts timely intervention efforts and undermines preventive strategies aimed at breaking the chain of transmission[9].

Recent advances in next-generation sequencing (NGS), biosensing technologies, and CRISPR-based detection platforms have demonstrated high sensitivity and specificity for viral diagnostics. Nevertheless, these emerging technologies often face challenges related to cost, throughput, operational complexity, and deployability in point-of-care (POC) or near-patient settings. Moreover, their performance under low viral load conditions and varying environmental parameters remains insufficiently validated [10].

METHOD

A flowchart is a graphic depiction that shows the steps, order, and logical procedures in a study from beginning to end. It typically takes the shape of a chart using common symbols (squares, diamonds, arrows) that make it simple for readers to comprehend the study's methodical flow. This is a picture of a flowchart showing how to use the tool.

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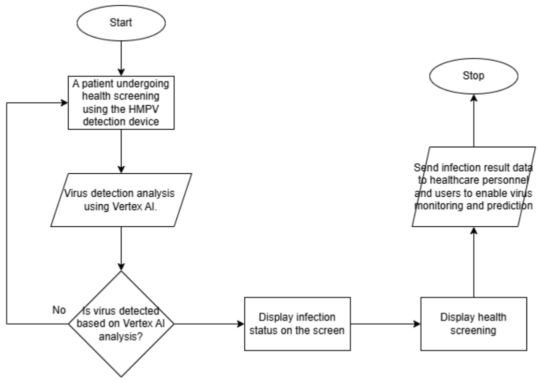

Figure 1 Flowchart

The process begins when a patient undergoes a health check using an HMPV device. Data from the device is then processed through the Virus Detection Scan stage, supported by Vertex AI technology. Once the scan is complete, the system displays the preliminary results in the application.

At this point, the system enters the decision-making stage of yes or no. If the result is yes, the system will display a notification on the screen that the patient is infected with the virus. After the patient is confirmed positive, the system performs an advanced virus detection scan to validate the data. The test results are then sent to the Bliv application for further processing.

At this stage, data is not only used as diagnostic results, but also for two main purposes: developing Artificial Intelligence (AI) to train and continuously improve the accuracy of artificial intelligence models using Vertex AI, and epidemiological monitoring to track and predict the rate of virus transmission. This enables early detection of potential outbreaks in an area.

If not, then the patient is directed back to the initial examination stage (looping) for re-examination or routine monitoring.

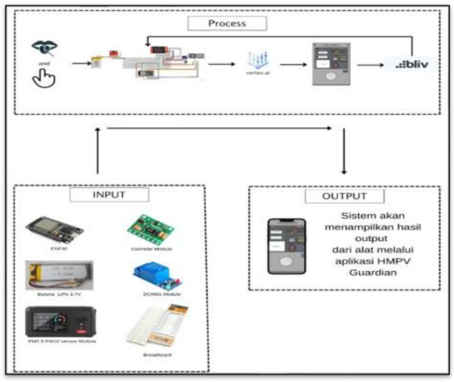

Figure 2 General Architecture

As can be seen in the image above, there are three parts: input, process, and output. The input stage of the system involves acquiring environmental data through several sensor units. Particulate parameters (PM2.5 and PM10) are detected by special sensors, while oxygen levels are measured using an oximeter module. All data from these sensors is then sent and consolidated by the ESP32 microcontroller as the main control unit.

After the entire data collection process is complete, the collected data enters the processing stage. The processing stage begins with raw data obtained from sensors, which is then sent to the Bliv server for storage. At this stage, analog or digital signals from sensors are converted into a data format that can be understood by the software system, which then becomes the basis for further action in detecting the presence of viruses or other health parameters. The processed data format at Bliv is as follows.

Table 1. Example of a normalized dataset

id	bpm	oksigen	suhu	Create_at
1	0	422	32.05	26/12/25 14.12
2	43	464	35.43	26/12/25 14.16
3	0	498	34.37	26/12/25 14.20
4	69	390	39.19	26/12/25 14.24
5	67	367	35.19	26/12/25 14.30
6	0	428	33.91	26/12/25 14.34
7	66	354	32.95	26/12/25 14.36
8	64	345	34.97	26/12/25 14.40
9	67	339	34.07	26/12/25 14.45
10	25	346	37.03	26/12/25 14.55

Once the data is prepared, a machine learning model is developed using the Vertex AI platform with the AutoML algorithm to analyze sensor data and identify patterns related to virus detection. AutoML is selected for its ability to simplify and accelerate model development by automating preprocessing and model construction, while continuously improving accuracy through learning from new data. After analysis, the results are transmitted to the Bliv platform for data management and storage, and the validated outputs are displayed on the HMPV Guardian Application. This workflow enables real-time health status monitoring for users via smartphones, while ensuring seamless synchronization between devices, AI cloud services, and the system database.

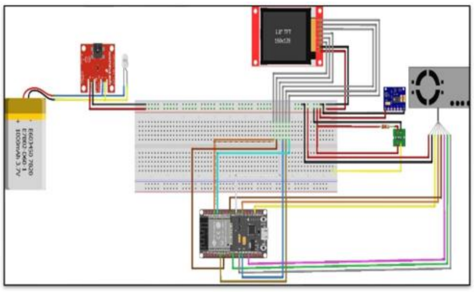

Figure 3 Tool Diagram

RESULT AND DISCUSSION

This research discussion begins with an evaluation of two key aspects, namely system calibration and instrument response time in producing analysis outputs. Testing began with the system initialization stage to ensure that all components, especially the connections between the ESP32 and all sensor modules, were functioning properly. Next, the sensor calibration stage, which involved PM2.5, PM10, oximeter, and temperature sensors using standard references, became the fundamental basis for ensuring data accuracy and stability before sampling. The next stages can be seen in the information table below.

Table 2. Testing Phase

Testing Phase	Test Procedure	Measured Parameters	Testing Objective
System Initialization	The HMPV Guardian device is turned on and the ESP32 is connected to all sensor modules.	Sensor and microcontroller connection status.	Ensuring that all components are functioning and connected properly.
Sensor Calibration	The PM2.5, PM10, oximeter, and temperature sensors are calibrated using standard references.	Baseline values for PM2.5, PM10, SpO2, and temperature.	Ensuring data accuracy and stability prior to sampling.
Environmental Data Acquisition.	The sensor collects environmental data simultaneously during the	Concentrations of PM2.5, PM10, oxygen levels, and temperature.	Collecting environmental data relevant to

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	testing period.		respiratory risk.
Local Processing	The sensor data is processed by the ESP32 microcontroller.	Integrated data from sensor readings.	Consolidate and prepare data for further analysis.
Data Transmission.	The data is sent wirelessly to the cloud system.	Delivery time and transmission success.	Testing the reliability of IoT communication.
Analysis with autoML	The data was analyzed using the Bliv and Vertex AI platforms.	Risk classification results.	Assessing the system's ability to recognize risk patterns.
Output and Notifications.	The system displays results and sends early warnings if thresholds are exceeded.	Risk status (safe/caution /high)	Evaluating the effectiveness of the system as a screening tool.
Response Time Evaluation.	Measurement of the duration from data acquisition to the display of results.	Response time (45 seconds–1 minute).	Assessing the speed of the system in delivering results.

Before integration into the system, each sensor module is tested individually. The table below summarizes the information, simple testing methods, and final status of each sensor, indicating that all components are functioning optimally.

Table 3. Test Result

No	Sensor Name	Status
1	PM2.5	Success
2	PM2.10	Success
3	Oxymeter Module	Success
4	Temperature Module	Success

After all sensors have been confirmed to be functioning and have reached a stable operational condition, the system as a whole is capable of producing monitoring and risk classification results in a relatively short time, namely around 45 seconds to 1 minute. This time frame covers the entire process, from data collection by sensors, data processing by the ESP32 microcontroller, to data transmission to cloud services for further analysis with the help of the Bliv and Vertex AI platforms. Thus, these findings show that the developed tool has an adequate and competent response time to function as a real-time and rapid environment-based health risk screening and monitoring system.

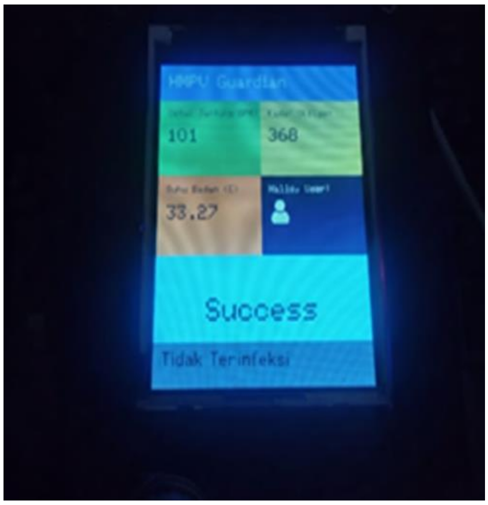

Figure 3 Success Test

The image above shows the interface of the HMPV Guardian health

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monitoring system. In the first test labeled Success, the system successfully detected and actively processed all of the user's vital parameters, as indicated by the appearance of a number in the Heart Rate (BPM) column of 101 and the values for Oxygen (O2) and body temperature. This indicates that the sensor is properly connected to the user's body and that the data has been successfully transmitted to the processing unit and successfully identified that the respondent's status is not infected with the virus.

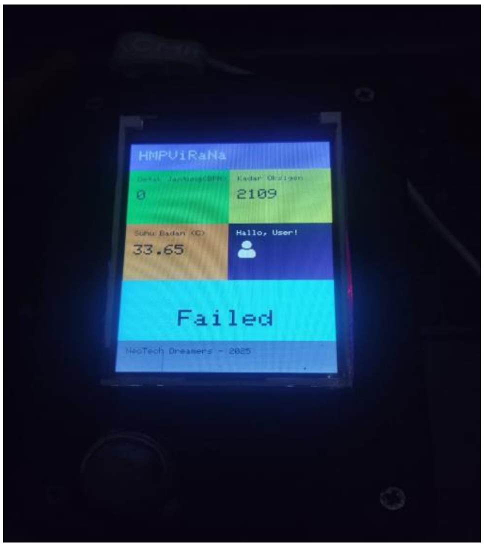

Figure 4 Failed Test

Conversely, in the second image labeled Failed, the system indicates a failure in the data collection process. This is clearly seen from the Heart Rate (BPM) reading, which shows a value of 0, indicating that the sensor failed to capture the pulse or that there was a disconnection in the hardware. Although the temperature and oxygen level readings still appear, the system automatically gives a failed status because the data read is incomplete or does not meet the specified health parameter validation criteria.

Table 4. Sample Total

No	Age Range	Sample	Status	Percentage
1	18 – 24 Years	60	Identified	10%
			Not Identified	90%
2	Over 25 Years	45	Identified	15%
			Not Identified	85%

Discussion of these results indicates that the developed tool performs well as a screening and early warning system, particularly in detecting environmental conditions that potentially increase the risk of respiratory tract infections. This is in line with previous studies stating that air quality, especially exposure to fine particles, plays a significant role in increasing susceptibility to respiratory viral infections.

The integration of artificial intelligence through Vertex AI enables the system to adaptively recognize risk patterns and provide early warning notifications when environmental parameters exceed certain thresholds. However, the test results also confirm that the system still has limitations in terms of sensitivity and classification accuracy, especially in conditions of low viral load infection. The system's dependence on the quality of input data leads to a potential increase in false positives, especially when there are temporary environmental disturbances.

Therefore, this tool cannot yet fully replace molecular diagnostic methods such as PCR, but it functions optimally as a tool to support initial grouping and environment-based risk monitoring, especially in areas with limited laboratory facilities.

Overall, these results and discussions indicate that the development of rapid diagnostic tools based on environmental sensors, IoT, and artificial intelligence is a relevant and promising approach to improving access to early detection of HMPV and strengthening respiratory tract infection prevention systems in the future.

CONCLUSION

With further development, including improvements in data processing algorithms, sensor optimization, and the integration of virus-specific biosensors, this system has the potential to enhance accuracy and reliability in supporting the control of HMPV transmission. However, this tool cannot yet fully replace molecular diagnostic methods such as PCR and is best utilized as a complementary solution for initial screening and environment-based risk monitoring, particularly in areas with limited laboratory infrastructure.

Overall, these findings indicate that the development of rapid diagnostic tools based on environmental sensors, Internet of Things (IoT) technology, and artificial intelligence represents a relevant and promising approach to improving access to early HMPV detection and strengthening future respiratory tract infection prevention systems.

Based on these conclusions, future research should focus on broader field validation, further integration of virus-specific biosensors, and optimization of artificial intelligence algorithms to improve detection accuracy. In addition, collaboration with healthcare providers and policymakers is recommended to support sustainable implementation of this system as an early screening and environment-based risk monitoring tool, particularly in regions with limited access to laboratory diagnostic facilities.

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