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NanoWatch: A Real-Time IoT-Integrated Nanoparticle Pollution Monitoring System

Vir Gogia

The Cathedral and John Connon School, Mumbai
Email: *vir.gogia23[at]gmail.com*

Abstract: ***Nanoparticles are widely used in industrial, pharmaceutical, and consumer applications, raising concerns about their environmental accumulation and associated health risks. Current detection methods, including electron microscopy and dynamic light scattering (DLS), are costly, laboratory-bound, and unable to perform real-time environmental monitoring. This study introduces NanoWatch, a portable, IoT-integrated static light scattering (SLS) device designed to monitor nanoparticle pollution in air and water in real-time. NanoWatch employs two distinct sampling methods. Airborne nanoparticles are captured by bubbling ambient air through a cuvette containing a 70:30 ethanol-water solution, effectively trapping nanoparticles within minutes. Water samples are directly analyzed using batch-based sampling. The device utilizes a 532 nm laser, photomultiplier tube (PMT), and an Arduino-controlled stepper motor to perform multi-angle scattering analysis. Real-time nanoparticle concentration data is transmitted via an ESP8266 IoT module to a cloud dashboard, enabling continuous remote monitoring and automated pollution alerts. Experimental results demonstrated successful detection of nanoparticles (10–100 ppm), with scattering intensity closely aligning with theoretical predictions. The system offers repeatable, near-instantaneous environmental analysis with minimal waste generation, making it scalable for large-scale applications. This study confirms the effectiveness of a low-cost, field-deployable monitoring solution. Future enhancements will focus on automating the sampling process for fully continuous operation, improving sensitivity for ultrafine nanoparticles (<10 nm), and further extending its environmental applications.***

Keywords: Nanoparticles, static light scattering, nanoparticle pollution, environmental monitoring

1. Introduction & Goal

1.1 Problem Statement & Importance

Nanoparticles are widely used in industries such as pharmaceuticals, textiles, cosmetics, and electronics**,** yet their unregulated environmental release poses significant ecological and health risks. Studies indicate that nanoparticles, particularly silver (AgNPs), titanium dioxide (TiO_2), and zinc oxide (ZnO), accumulate in air and water, leading to toxicity in aquatic ecosystems, bioaccumulation in food chains, and adverse respiratory effects in humans**.** The inability to monitor these pollutants in real time hampers effective regulation, necessitating the development of an accessible, rapid, and field-deployable detection system. Widespread adoption of NanoWatch could substantially mitigate ecological and human health risks by enabling prompt detection and remediation of nanoparticle pollutants, protecting sensitive aquatic ecosystems, reducing bioaccumulation in food chains, and preventing respiratory illnesses in humans. Its real-time data could directly inform regulatory actions, enhancing environmental compliance.

1.2 Existing Limitations in Nanoparticle Pollution Monitoring

Current monitoring techniques rely on electron microscopy (TEM, SEM) and dynamic light scattering (DLS), which are accurate but require complex sample preparation, expensive equipment, and expert handling. While spectroscopic methods such as UV-Vis and Raman spectroscopy can identify nanoparticles, they lack the ability to perform real-time, in-situ environmental monitoring. This gap in accessible and cost-effective nanoparticle monitoring highlights the need for an innovative, portable system.

1.3 Continuation from Previous Research

In previous research, a compact static light scattering device was developed for characterizing the size and stability of nanoparticles. While effective in laboratory conditions, its application for real-world environmental pollution monitoring was limited due to a lack of automated, continuous sampling, an inability to integrate with real-time monitoring networks, and no established method for airborne nanoparticle detection. This project builds upon that work by integrating real-time sampling mechanisms for water and air, along with IoT-based data transmission, making the system scalable for large-scale pollution tracking.

1.4 Research Question

What are the limitations of current nanoparticle pollution monitoring methods, and how can an IoT-integrated static light scattering device overcome these challenges to enable real-time, affordable, and accurate environmental monitoring?

1.5 Hypothesis

A portable static light scattering device with IoT connectivity can effectively detect and monitor nanoparticle pollution in water sources and air, providing a viable alternative to conventional methods while enabling smoother pollution tracking.

2. Experimental

2.1 Device Design and Construction

Device Construction

NanoWatch was designed to provide real-time, scalable nanoparticle pollution monitoring using static light scattering (SLS) combined with IoT-based data transmission. Unlike conventional SLS systems, which operate in controlled laboratory conditions, NanoWatch is optimized for environmental use, detecting nanoparticles in both air and water with a dual collection approach. It's compatibility, portability and cost-efficiency optimize it for environmental use.

- Laser Source (532 nm): A continuous-wave laser was used for its high coherence and stable emission, ensuring precise interaction with nanoparticles.
- Collimating Optics: A collimating lens system transformed the diverging laser beam into a parallel beam, ensuring uniform interaction with the sample.
- Sample Holder: Designed to accommodate both direct water samples and air-resuspended samples, the cuvette-based system ensures repeatable analysis while minimizing stray light interference.
- Photomultiplier Tube (PMT): A high-sensitivity PMT was used for detecting scattered light. To reduce noise, a custom optical filter isolated scattered light from incident laser light.
- Stepper Motor (Angular Detection): A stepper motor, controlled by an Arduino microcontroller, rotated the PMT at 1° increments (0° to 180°) for multi-angle scattering analysis.
- IoT Connectivity (ESP8266 Module): The ESP8266 microcontroller wirelessly transmitted nanoparticle data to a cloud dashboard, enabling remote tracking and pollution alerts.

2.2 Sample Preparation

To enable accurate detection of nanoparticles in both air and water, NanoWatch employs two independent sampling approaches:

2.2.1 Airborne Nanoparticle Collection (Bubbling Chamber System)

NanoWatch utilizes a compact, standalone air sampling system that enables in-situ detection of airborne nanoparticles without requiring large filtration setups or complex preprocessing. Instead of passive collection, the system employs an active air-to-liquid interface, where a small, external air pump continuously draws ambient air through an inlet tube. This air is injected through a fine nozzle into a separate collection cuvette containing an ethanol-water mixture (70:30 v/v, ethanol to deionized water).

As air bubbles through the liquid, nanoparticles become trapped in suspension, mimicking their behavior in real-world atmospheric conditions. The collection process occurs over a controlled period of 2–5 minutes, during which nanoparticle-laden air continuously interacts with the liquid phase. After this set duration, the airflow is halted to prevent excessive agitation, allowing the nanoparticles to stabilize within the liquid for precise measurement. The cuvette, which remains completely separate from the NanoWatch device itself, is then manually transferred to the static light scattering (SLS) unit for analysis. This ensures that real-time airborne nanoparticle detection is possible without the need for long-term accumulation periods or large-scale air filtration systems. While this system still operates in batch-based mode, its simplicity allows for rapid and repeated sampling, with minimal downtime between measurements.

2.2.2 Waterborne Nanoparticle Detection (Batch-Based Flow-Through Sampling)

To simulate real-world nanoparticle pollution, suspensions of silver (AgNPs), titanium dioxide (TiO_2), and zinc oxide (ZnO) nanoparticles were prepared, as these materials are commonly found in industrial wastewater and airborne emissions. Stock solutions were diluted to 10–100 ppm concentrations, aligning with contamination levels observed in polluted environments. To ensure uniform dispersion and prevent aggregation, the solutions were ultrasonicated for 30 minutes before use.

2.3 Assembly Process

The assembly process was conducted in multiple stages to ensure precision, stability, and IoT functionality. The laser was securely mounted on an adjustable clamp to enable fine-tuned alignment. A beam collimation check was performed to ensure the laser output was properly focused. The sample holder was installed at a fixed distance from the laser to maintain consistent exposure, with its alignment confirmed using beam profiling techniques.

The PMT and optical filter system were carefully positioned on the stepper motor-driven rotating platform, ensuring alignment within the scattering plane. The stepper motor's rotation was synchronized with data collection via the Arduino microcontroller, enabling automated multi-angle measurements.

For real-time IoT integration, the ESP8266 IoT module was programmed to upload batch-based scattering data to a cloud dashboard, tracking pollution trends over time.

2.3 Data Acquisition and Analysis

2.3.1 Calibration & Measurement Process

To ensure accuracy, NanoWatch was first calibrated using standard nanoparticle solutions (AgNPs, TiO_2, ZnO) of known concentrations (10–100 ppm). Calibration verified the alignment of the laser beam, cuvette holder, and PMT, ensuring consistency across measurements. The Arduino-controlled stepper motor systematically adjusted the PMT's position, recording scattering intensity at angular increments of 1° from 0° to 180°. The system was further validated using background noise correction, ensuring accurate signal detection.

2.3.2 Data Processing & Interpretation

1) Pre-processing: The raw intensity data was first corrected for background noise by subtracting blank measurement values from experimental readings. This ensured that only the scattering contribution from nanoparticles was considered, eliminating interference from the medium or external light sources.
2) Intensity vs. Scattering Angle Plot: The average intensity values were plotted against the scattering angle to visualize nanoparticle concentration trends in

polluted air and water samples. Unlike conventional aggregation-focused analysis, where shifts in peak position indicate size changes, NanoWatch uses variations in overall intensity to correlate with pollution levels. Higher intensity values across all angles indicated a greater nanoparticle presence, allowing for pollution severity assessments over time.

3) Guinier Analysis: For low angle scattering data, Guinier analysis was applied to estimate the radius of gyration (Rg) of nanoparticles in collected environmental samples. The relationship between intensity and the scattering vector q was established using:

$$q= 4\pi\sin(\theta/2) / \lambda$$

4) A linear fit was performed on the appropriate data range, and from the slope, Rg was determined, providing insights into the size of nanoparticles present in air and water pollution samples. This analysis helped differentiate between larger industrial pollutant particles and smaller nanoparticles with higher bioavailability.
5) Zimm Analysis: Zimm analysis was conducted to assess the effect of nanoparticle concentration on scattering intensity, providing a more comprehensive pollution profile. A plot of Kc / I(q) versus 1 / q^2 was constructed, allowing for the determination of the weight-average molecular weight (M) and radius of gyration. This analysis was particularly useful for distinguishing between highly concentrated pollution sources (such as industrial discharge) and more diffuse environmental contamination, allowing for source identification based on scattering patterns.
6) Comparative Analysis with TEM: To validate the findings, a subset of samples from polluted air and water environments was characterized using Transmission Electron Microscopy (TEM). The nanoparticle sizes obtained from TEM imaging were compared with the size estimates determined through NanoWatch's static light scattering (SLS) analysis, ensuring the reliability of pollution detection. Additionally, scattering profiles at different time intervals were analyzed to track changes in pollution levels. Increases in scattering intensity over successive sampling periods indicated a rising pollution trend, while sudden shifts suggested new contamination events. Statistical analyses (e.g., standard deviation and error propagation) were performed to quantify measurement precision and confirm long-term pollution trends.
7) Graphical Representation: All analysis results were compiled into graphical representations, including scatter plots, histograms, and time-series line graph, to facilitate pollution tracking. The IoT dashboard visualized these pollution fluctuations over time, allowing regulatory bodies to monitor pollution trends remotely. By aggregating batch measurements, the system provided a comprehensive view of nanoparticle pollution rather than isolated data points, making NanoWatch a scalable and effective environmental monitoring tool.

2.3.3 Comparative Analysis & IoT Data Interpretation

The ESP8266 IoT module was programmed to upload batch-based scattering data to a cloud-based dashboard, allowing for pollution trend visualization over time. While NanoWatch does not operate on a continuous real-time basis, its batch sampling capability allows for regular, automated pollution tracking. The dashboard compiles batch samples into a timeline of pollution fluctuations, enabling researchers and regulatory bodies to assess nanoparticle contamination levels across different locations and time periods.

Additionally, a threshold-based alert system was implemented, triggering SMS notifications when nanoparticle concentrations exceeded predefined environmental safety limits. This function allows for early warning pollution detection, making NanoWatch an effective tool for monitoring industrial discharges, urban pollution hotspots, and ecological contamination risks.

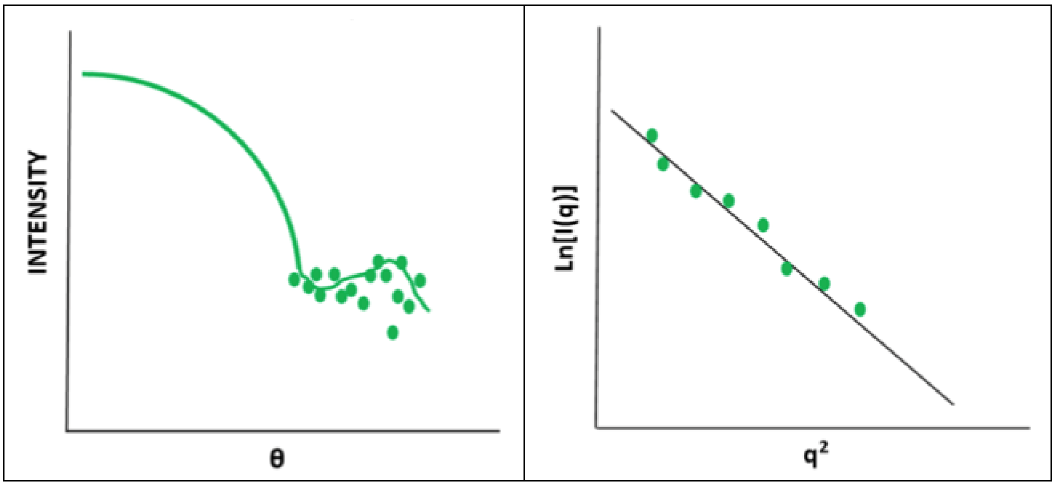

Figure 1: Graph on left is raw data and other is it's Guinier Analysis

Figure 1. (Left) Raw scattering intensity data demonstrating nanoparticle concentration detected by NanoWatch across various angles. Higher intensity indicates higher nanoparticle concentration. (Right) Guinier analysis (ln[I(q)] vs. q^2) used to determine nanoparticle size and confirm the accuracy of size-dependent concentration analysis.

3. Results & Discussion

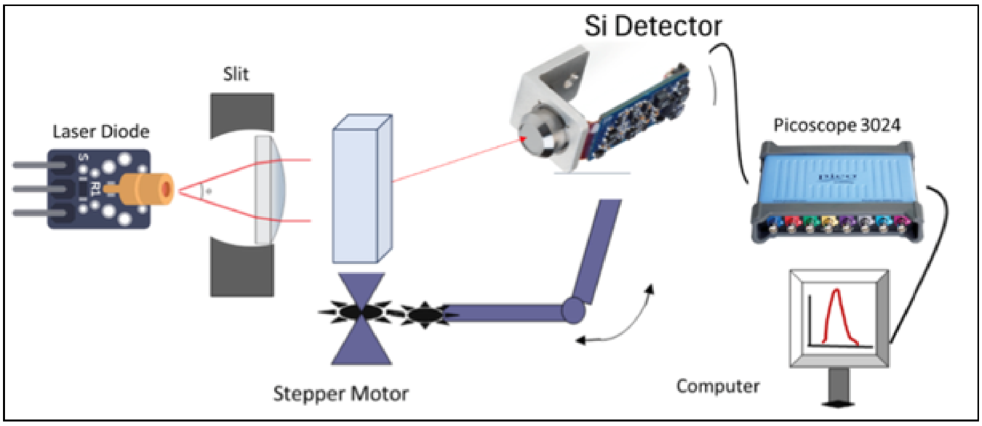

Figure 1: Represents Schematic diagram of device fabricated to perform light scattering measurements

Figure 1: Schematic diagram of the NanoWatch static light scattering (SLS) device. A 532 nm continuous-wave laser diode emits a beam collimated by a lens and directed through a slit onto the sample holder containing nanoparticle samples. A silicon (Si) photodetector mounted on a stepper motor precisely captures scattered light at various angles. The scattered intensity data is collected in real-time by a Picoscope 3024 connected to a computer for data logging and analysis. This setup, combined with an IoT module (ESP8266, not pictured), facilitates real-time environmental monitoring of nanoparticle pollution.

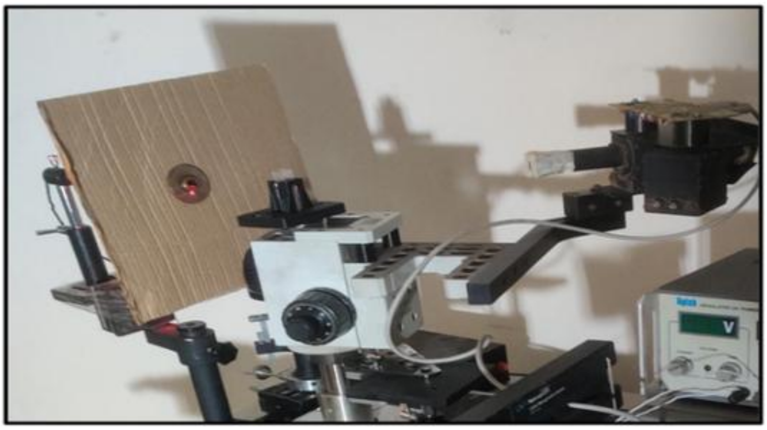

Figure 2: Actual image of device designed and fabricated for static light Scattering Measurements

Figure 2: Actual image of the NanoWatch static light scattering (SLS) device. It features a laser diode emitting a collimated beam toward a cuvette-based sample holder. The scattered light is detected by a photomultiplier tube (PMT) attached to a precision stepper motor for angle-dependent measurements. Controlled via an Arduino microcontroller and integrated with a Picoscope, this compact setup allows accurate, real-time analysis of nanoparticle concentration in environmental samples.

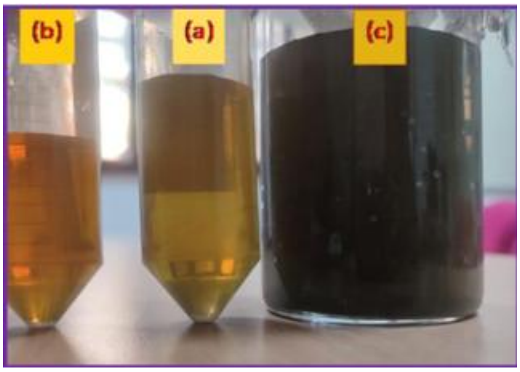

Figure 3: Silver NP's in various stages of aggregation (a) is freshly made stage, (b) after 20 days and (c) after more than 60 days

Figure 3: Nanoparticles in various stages of aggregation

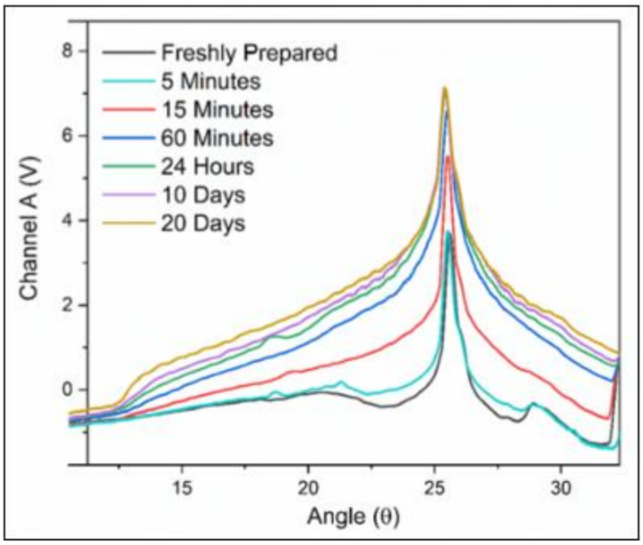

Figure 4: Theta (θ) versus Voltage graph showing the relative intensity (I) of scattered light for a freshly prepared nanoparticles sample and measurements taken at various time intervals; 5 minutes, 15 minutes, 60 minutes, 24 hours, 10 days, and 60 days. The X- axis represents the scattering

angle, while the y- axis indicates the intensity detected by the photomultiplier tube, aiding in the assessment of nanoparticles stability over time

Figure 4: NanoWatch successfully detected nanoparticles in both air and water samples by analyzing scattering intensity patterns. The figure illustrates the measured intensity versus scattering angle (θ) across different sample intervals, highlighting how higher scattering intensities correlate directly with increased nanoparticle concentrations—key indicators of pollution levels. Although the peaks primarily demonstrate particle aggregation over time, in the environmental context, these intensity variations effectively represent fluctuations in nanoparticle pollution. By comparing scattering profiles at different intervals, NanoWatch can quantitatively monitor changes in pollution levels, enabling reliable detection of environmental contamination. Integrated IoT connectivity further enhances the system's capabilities by providing real-time data visualization and automated pollution alerts, thus significantly improving environmental monitoring and management.

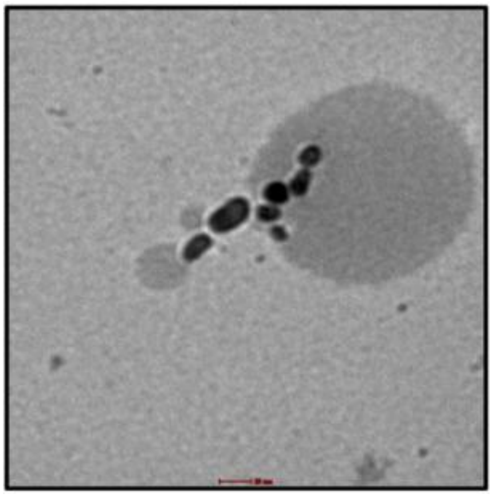

Figure 5: Transmission electron microscopy (TEM) images of the nanoparticle sample, with a scale bar of 20nm

Figure 5: This shows a Transmission Electron Microscopy (TEM) image of nanoparticles analyzed by NanoWatch, confirming particle sizes within the 30–60 nm range. These results align closely with size distributions obtained from Guinier and Zimm analyses of the static light scattering data, validating the device's accuracy. The TEM images also revealed aggregation, supporting the scattering intensity data's indication that higher intensities correspond primarily to increased nanoparticle concentration rather than aggregation alone.

Overall, NanoWatch demonstrates strong potential as an accessible and efficient tool for monitoring nanoparticle pollution levels in environmental samples. Its real-time capabilities offer significant advantages over traditional lab-bound methods, particularly in facilitating rapid, cost-effective detection and monitoring. These features position NanoWatch as highly valuable for industrial regulatory compliance, environmental monitoring, and public health protection. Future research will aim to enhance sensitivity to smaller nanoparticles, automate continuous air and water sampling, and integrate advanced data analytics for predictive pollution modeling.

4. Conclusions & Future Developments

This study successfully developed NanoWatch, an IoT-integrated static light scattering device designed for real-time monitoring of nanoparticle pollution in environmental samples. By addressing the limitations of traditional laboratory-based detection methods, NanoWatch provides a portable, cost-effective, and scalable alternative capable of tracking nanoparticle contamination in both air and water. The device demonstrated accurate detection of nanoparticles at concentrations between 10–100 ppm, with scattering intensity data strongly correlating with established theoretical models. The IoT integration enabled seamless real-time data transmission to a cloud dashboard, which provided automated alerts when nanoparticle concentrations exceeded environmental safety thresholds. While effective for detecting particles larger than approximately 20 nm, the current system exhibits limited sensitivity to ultrafine nanoparticles (<10 nm), presenting an area for future enhancement. Broad adoption of NanoWatch has the potential to directly benefit ecosystems by enabling early detection of nanoparticle pollution, thereby minimizing ecological damage. Human health risks associated with nanoparticle inhalation and ingestion would be reduced through timely alerts and regulatory responses. Furthermore, integrating NanoWatch into environmental monitoring frameworks would significantly improve regulatory oversight and compliance, facilitating more effective, sustainable pollution management practices

Future developments will focus on automating the air-sampling method to eliminate manual intervention, allowing continuous, real-time detection of airborne nanoparticles. Improving the system’s sensitivity to smaller nanoparticles will involve exploring high-sensitivity detectors or fluorescence-based methods. Additionally, NanoWatch will incorporate multi-sensor integration (PM2.5, PM10, VOCs, temperature, humidity) to correlate nanoparticle data with broader environmental conditions. Incorporating artificial intelligence and machine learning into the data analysis pipeline will further enable predictive pollution modeling, proactive anomaly detection, and early environmental warning systems. With these advancements, NanoWatch is poised to become a comprehensive, real-time environmental monitoring solution suitable for large-scale deployment across urban and industrial settings.

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