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Introduction to "Advances in Nanomaterials for Sensors in Early Disease Diagnosis"

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We are delighted to introduce the themed collection in *Sensors & Diagnostics* entitled "*Advances in Nanomaterials for Sensors in Early Disease Diagnosis*". This collection highlights recent progress in the development and application of advanced nanomaterials for sensor technologies, aimed at early disease detection, with nine contributions that collectively explore a diverse range of nanomaterial platforms for the precise detection of biological biomarkers, underscoring their potential to transform early disease diagnosis.

Among the contributions, Lee *et al.* (https://doi.org/10.1039/D5SD00100E) present a comprehensive review of emerging trends in aerogel technologies for sensing and biosensing applications. Aerogels have recently gained significant attention in the sensing field owing to their exceptional physicochemical properties, including low density, tuneable porosity, high specific surface area with tailorable functionalities, and favourable biocompatibility. Consequently, aerogel-based sensor technologies are advancing rapidly. This timely review highlights recent developments in aerogel synthesis strategies, the design of novel aerogel composites, and the integration of aerogels into sensor platforms for biosensing, biomarker detection, smart and wearable sensors, and microfluidic devices. In addition, the authors critically evaluate the mechanisms underpinning enhanced sensor performance and discuss opportunities for real-time biomolecule monitoring, as well as the development of portable, cost-effective lab-on-a-chip systems through the integration of aerogel-based sensors with microfluidic technologies.

Early detection is critical in cancer diagnostics, as it enables timely intervention, improved treatment outcomes, and increased patient survival rates. Dennany *et al.* (https://doi.org/10.1039/D5SD00110B) report the potential translational application of electrochemiluminescence (ECL) as an analytical tool for imaging chemotherapeutic agents. In this study, the authors demonstrate a proof-of-concept for the *in vitro* detection of the chemotherapeutic drug gemcitabine (GEM), released *via* a heat-triggered mechanism from the surface of hybrid iron oxide–gold theranostic nanoparticles in pancreatic cancer cells. Notably, this work represents the first real-time detection of GEM released from hybrid iron oxide–gold nanoparticle platforms. The authors also provide a detailed discussion of the challenges associated with analysing complex biological matrices and how these challenges were addressed, highlighting the robustness, translational potential and future outlook of the ECL-based approach. Another communication by Lee *et al.* (https://doi.org/10.1039/D5SD00108K) reports the development of a compact, image-based flow cytometry system that integrates acoustic focusing with machine-learning-driven image analysis for CD4 and CD8 cell detection. In this work, the authors demonstrate the rapid detection of stained CD4 and CD8 cells by directing cells along an acoustically defined focal plane, offering an alternative to conventional hydrodynamic focusing and enabling a more compact system configuration. The custom-built platform is capable of detecting up to three fluorescently labelled signals, while the integration of a machine-learning-based image capture and analysis algorithm enables automated cell segmentation and quantitative analysis of the acquired image data.

Reflecting the central theme of this special issue, five articles address the application of advanced nanomaterials for the detection of a range of biological analytes. Among these, Sharma *et al.* (https://doi.org/10.1039/D5SD00165J) reported the development of a low-cost, rapid, and scalable electrochemical biosensor for point-of-care (POC) monitoring of rifampicin during

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tuberculosis therapy. In this study, the authors demonstrate that integrating a highly selective molecularly imprinted polymer (MIP) with a highly porous gold (HPG) nanomaterial on a disposable printed circuit board (PCB) electrode significantly enhances the electroactive surface area while providing excellent resistance to biofouling. This design enables reliable detection of rifampicin in complex biofluids. The sensor achieves a clinically relevant detection range of 8–24 μg mL^{-1}, with a limit of detection (LOD) of 0.848 μg mL^{-1} and a limit of quantification (LOQ) of 1.31 μg mL^{-1}. Notably, this platform overcomes key barriers to widespread therapeutic drug monitoring (TDM) by eliminating the need for costly instrumentation and complex sample pre-treatment, enabling POC testing at an estimated cost of £0.09 per assay.

Another article by Thenmozhi *et al.* (https://doi.org/10.1039/D5SD00114E) reports the design and development of a $Ti_3C_2T_x$ MXene nanomaterial platform as an efficient electrochemical sensor for the sensitive and selective detection of hydrogen peroxide (H_2O_2). The authors emphasise the importance of surface engineering of $Ti_3C_2T_x$ nanosheets in enabling non-enzymatic H_2O_2 sensing. Specifically, EDC/NHS coupling chemistry was employed to selectively immobilise the toluidine blue redox mediator onto the COOH–$Ti_3C_2T_x$ surface. Notably, the resulting electrode exhibited excellent stability and reproducibility, along with high selectivity and sensitivity (0.61 μA μM^{-1} cm^{-2}) and a low detection limit of 1.5 μM for H_2O_2 detection.

Another contribution from Prasad *et al.* (https://doi.org/10.1039/D5SD00038F)) reports the development of a ferrocene-encapsulated metal–organic framework (MOF)-based sensor for monitoring metabolic processes through the detection of four physiologically relevant volatile organic compounds (VOCs): ethanol, isopropanol, acetic acid, and acetone. In this study, the authors employ zeolitic imidazolate framework-8 (ZIF-8) as the nanomaterial platform, with ferrocene encapsulation enhancing the electrochemical properties of the sensor. The sensor was evaluated for its ability to detect ethanol (100–1500 ppm), isopropanol (20–200 ppm), acetic acid (1–10 ppm), and acetone (50–1000 ppm), demonstrating the material's sensing performance, electrochemical transduction mechanism, and overall detection capability in a proof-of-concept setting.

Similarly, DeMauro *et al.* (https://doi.org/10.1039/D5SD00002E) demonstrate a novel electronic biosensing platform based on microfabricated nanowell impedance sensors, enabling rapid POC diagnosis of SARS-CoV-2 (COVID-19). The nanowell sensor was fabricated on a silica substrate using a series of microfabrication processes and features a 5 × 5 nanowell array functionalised with specific antibodies. Real-time impedance changes within the nanowell array allow testing results to be obtained within ten minutes using minimal sample volumes (<5 μL). The platform achieves a detection limit of 0.2 ng mL^{-1} (1.5 pM) for SARS-CoV-2 spike proteins and successfully differentiates Middle East respiratory syndrome coronavirus (MERS-CoV) spike proteins, demonstrating high analytical specificity. Within the concept of real-time disease monitoring, Jha *et al.* (https://doi.org/10.1039/D5SD00027K) report a handheld, non-invasive optical biosensor for salivary glucose monitoring, in which glucose oxidase and peroxidase, together with 4-aminoantipyrine and phenol, are co-immobilised on a paper-based strip incorporating a cellulose-filled fluidic channel to remove interferents and regulate saliva flow. The device initially measures salivary glucose levels (SGL) and, following software integration of clinical correlation equations, predicts equivalent blood glucose levels (BGL). The biosensor demonstrates a clinically relevant detection range of 14.5–213 mg dL^{-1}, a sensitivity of 10.6 counts per mg dL^{-1}, a LOD of 14.5 mg dL^{-1}, and a response time of 5 minutes. Clinical validation against a commercial glucometer revealed strong correlations between SGL and BGL for both diabetic and non-diabetic subjects under fasting and postprandial conditions. This saliva-based biosensor represents a low-cost, user-friendly, and painless POC alternative to conventional blood glucose monitoring, with strong potential for real-world diabetes management.

In their study, Paik *et al.* (https://doi.org/10.1039/D4SD00350K) report the green synthesis of carbon dots (4–8 nm) derived from *Azadirachta indica* seed kernels and investigate their application in heavy-metal ion detection. These waste-derived carbon dots function as fluorescent nanoprobes capable of detecting inorganic contaminants over a concentration range of 5–120 μM, owing to their strong photostability and excitation-dependent emission in aqueous media. The rapid and sustainable synthesis approach offers high selectivity and sensitivity. Notably, the carbon dots exhibit preferential interaction with Cd^{2+} and As^{3+} ions, resulting in significant fluorescence quenching of 27% and 30%, respectively, while fluorescence enhancement is observed in the presence of Cu^{2+} and Cu^{+} ions. This distinctive fluorescence response enables the selective identification and discrimination of multiple metal ions, including Al^{3+}, Cd^{2+}, Mn^{2+}, Ni^{2+}, Co^{2+}, Cu^{2+}, and Cu^{+}, with detection limits spanning 5–120 μM, demonstrating the potential of this low-cost, sustainable nanomaterial platform for environmentally relevant sensing application.

In conclusion, this themed collection highlights the transformative role of advanced nanomaterials in the next generation of sensor technologies for early disease diagnosis. Collectively, the contributions demonstrate how rational nanomaterial design, surface engineering, and system integration can deliver highly sensitive, selective, and scalable sensing platforms across a broad range of diagnostic applications. These studies underscore the translational potential of nanomaterial-enabled sensors to address pressing clinical and societal needs. We anticipate that the insights and innovations presented in this

collection will inspire further interdisciplinary research and accelerate the development of robust, accessible, and patient-centred diagnostic technologies for early disease detection.