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REVIEW ARTICLE

Microfluidic devices to monitor water pollution

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Abstract

Microfluidic devices offer a promising future for monitoring water pollution caused by heavy metals, especially as the world continues to develop and the dangers of pollutants increases. This highlights the importance of developing these devices. These devices operate within the dynamics of fluids and quantify pollutants with numerous advantages, such as high sensitivity and specificity. They can also be integrated with mini sensors alongside analytical techniques. This study provides a brief overview of the types of microfluidic devices, such as polydimethylsiloxane (PDMS) and microfluidic paper-based (μPADs), and their application in pollutant detection. Microfluidic devices are associated with analytical methods such as spectrometric, colorimetric, and electrochemical techniques. Their importance lies in their simple manufacturing, rapid detection capabilities, and portability. Additionally, these devices can be updated to meet current needs in water pollution detection by integrating various analytical methods and enhancing these methods with programs that provide on-site results. There for microfluidics are currently of great importance due to their ease of manufacturing and applicability to various analytical methods, particularly for detecting pollutants in water. Many studies highlight the extraordinary potential of paper-based devices, which are the easiest to manufacture among all microfluidic devices and are not subject to stringent engineering and physical constraints. Most importantly, they can utilize colorimetric detection methods, providing instant results visible to the naked eye. This study demonstrates these advantages and suggests the potential for expanding their applications in medical, environmental, and biological fields.

Keywords

Microfluidic devices; water pollution; heavy metals; LOC; microfluidic paper-based; PDMS

Introduction

Water is an essential resource for supporting life on Earth, and access to clean water is crucial for both humans and the ecosystem. However, over the past few decades, water quality has been adversely affected by steady population growth, rapid industrialization, expanding metropolitan areas, and irresponsible environmental practices. The environment encompasses the immediate surroundings in which humans, plants, animals, and microorganisms reside and carry out their activities. The Earth consists of 3 main components: land, atmosphere, and water. The Earth's system is defined by 4 interrelated spheres: the biosphere (comprising living species),

the atmosphere (consisting of air), the lithosphere (including land), and the hydrosphere (covering water). These spheres work together synergistically, operating in perfect harmony (1).

The issue of water contamination has become more apparent, resulting in significant ecological and environmental challenges. The lack of consideration for environmental consequences in industrial production has led to increased water and air pollution, as well as soil degradation. Additionally, it has contributed to major global issues such as acid rain, global warming, and ozone depletion (2). The use and disposal of numerous chemicals commonly employed in medicine, industry, agriculture, and even household products (3) further exacerbates the problem. Water pollution involves both organic materials and heavy metals. The organic materials include benzene, phenol, alcohol, naphthalene, and anthracene, among others (4).

Heavy metals are among the most dangerous and toxic pollutants. Therefore, it is important to first understand the term “heavy metals”. “Heavy metal” is a term used to describe metallic elements with a high density, often exceeding 4 g/cm^3. Examples include arsenic, chromium, cobalt, nickel, copper, zinc, selenium, silver, cadmium, antimony, mercury, thallium, and lead (5). Some metals are essential for metabolic functions in the human body, while others can lead to acute and chronic disorders (6). Heavy metal ions pose significant concern as common pollutants discharged into the environment. Both natural processes and human activities continually release these toxic metallic elements into the water sources (7). Although certain heavy metals are essential for biological functions, many are non-essential and can be harmful in elevated concentrations (8). Metals exhibit varying degrees of toxicity, which refers to their ability to cause adverse effects on living organisms. The persistence presence of heavy metals in the environment exacerbates the risks they pose to the health of living organisms. Toxicity levels increase in acidic and nutrient-deficient environments, particularly in locations with poor soil structure like mining sites (9). Male reproductive function is vulnerable to various environmental and occupational factors, though only a few have been well identified. Heavy metals notably contributes to reduced male fertility (10). Additionally, neurotoxicity resulting from exposure to high levels of heavy metals leads to serious conditions such as neurological disorders like Alzheimer's and Parkinson's disease (11), gastrointestinal disorders (12), increased cancer risk (13), chronic kidney disease (14), anaemia (15), cardiovascular infections (16), and metabolic syndrome, including hypertension and obesity (17).

There are several traditional treatment methods available to remove heavy metals from polluted water sources, including adsorption, coagulation, ion exchange, chemical precipitation, membrane filtration, and electrochemical technologies .The selection of these methods depend on their efficiency, practicality, cost-effectiveness, environmental impact, and operational challenges, among other factors (18).

Due to their high toxicity and association with numerous serious diseases and environmental damage, several analytical techniques are commonly used to detect heavy metals in wastewater samples. These techniques include atomic absorption spectrometry (AAS), inductively coupled plasma atomic emission spectrometry (ICP-AES), and inductively coupled plasma mass spectrometry (ICP-MS). However, these methods require the expertise of highly trained technicians for proper operation and maintenance, which contributes significantly to the overall cost of analysis. Additionally, the expenses associated with collecting, transporting, and processing samples vary depending on the frequency of sampling required (19). The cost of water monitoring is significantly influenced by transportation and labour charges (20).

New technology trend now includes microfluidic technology, which enables rapid and cost-effective on-site analysis of samples with minimal reagent consumption. This innovative approach saves time in protocol, lowers the risk of sample loss or contamination, and reduces costs by eliminating the need for bulky and expensive laboratory instrumentation (21).

The main objective of this review is to explore the role of microfluidic devices in detecting water pollution, highlighting the challenges and limitations faced by this technology. It also emphasizes the significance of microfluidic devices due to their ease of use and manufacture, as well as their capability to integrate with various analytical methods. Of utmost importance is the comparison of different types of these devices and outlining strategies for their further development to achieve rapid and accurate results.

Microfluidic devices

Microfluidics involves the study of fluid flow within devices ranging in sizes from mm to µm. These devices can handle fluid volumes ranging from nano to microliters (22). They offer several advantages across diverse fields such as biology, chemistry, pharmaceuticals, and environmental monitoring. These advantages include faster reaction times, precise process control, reduced waste generation, compact system design, scalability, cost-effectiveness, and disposability (23). However, microfluidic devices also face several challenges. One of these challenges is achieving effective mixing, which is crucial for sample dilution, reagent homogenization, and chemical or biological reactions (24). Another challenge is maintaining laminar flow, where fluids flow smoothly in parallel streams without mixing, characterized by a Reynolds number (Re) below 2100 (25).

Historically, microfluidic devices were primarily made from silicon and glass. However, in recent years, there has been increasing interest in polymer materials due to their potential for lower manufacturing costs and disposability. Various polymers such as poly (methyl methacrylate) (PMMA), poly (dimethylsiloxane) (PDMS), polycarbonate (PC), polyester, polystyrene (PS), and poly (ethylene terephthalate) (PET)(26). As well as paper-based microfluidic devices, have been explored. Several fabrication techniques are used in the production of

microfluidic devices, including laser micromachining, soft lithography, 3D printing, hot embossing, and wax printing.

Soft lithography is a collection of low-cost techniques for replicating patterns-from masters generated by photolithography, machining, or other methods-onto a range of substrates (27) it is Inexpensive and suitable for not only planar, but also non-planar surfaces, soft-lithography also provides a very good resolution (~35 nm) (28) suitable to with Polydimethylsiloxane (PDMS) (29)

While 3D printing Known as a set of additive manufacturing techniques, which can create solid three-dimensional (3D) objects layer-by-layer under precise digital control (30) characterized with

Quick and simple computer-aided design (CAD) to manufacturing and ability, printing parts with almost any geometric complexity (31) also suitable for manufacture of PDMS microfluidic devices (32) Another techniques is Laser micro machining one such technique which produces intricate shapes with the help of lasers (33)with Good quality, high resolution, high production yields, high precision, good tolerances, high processing speeds, low thermal damage, high flexibility, excellent reproducibility, economically attractive (34) laser micro machining use to fabricate Polymethyl methacrylate(PMMA) and PDMS microfluidic devices (35).

Hot embossing refers to a technique of imprinting micro or nano structures on a substrate with a master mold (36) which it is low-cost, high-throughput method to mold thermoplastics with control of feature dimensions in the nanoscale over a large area for thermoplastic cell culture materials (37) used with PMMA and PDMS materials (38). In addition, there is wax printing technique includes printing wax on the surface of paper using a solid ink printer, then a brief includes heating step to melt the wax into the paper (39) it is Simple and low-cost which used wax commercially available and is inexpensive (40) special for fabricate Paper-based microfluidic devices (µPADs) (41).

Microfluidic devices, particularly Lab-On-Chip (LOC) devices, have proven effective in continuous monitoring of contaminants in wastewater, serving as a perpetual environmental alert system. Integration of these technologies with wireless connectivity enhances their capacities to remotely adjust acquisition parameters and facilitate data transfer (42). This analysis specifically focuses on two categories of microfluidic devices: PDMS and paper-based microfluidic systems (43).

Paper-based microfluidic devices

Microfluidic paper-based analytical devices (µPADs) have gained considerable popularity following ground-breaking studies by the Whitesides group. Paper platforms offer several advantages, including affordability, portability, and ease of disposal (44) Typically, a paper sheet is modified to create hydrophobic regions while leaving other areas hydrophilic. The hydrophilic channels in the sampling area enable precise wicking of liquid solutions through capillary action (45).

To enhance the effectiveness of paper microfluidics, it would be advantageous to develop materials and systems that retain the benefits of paper while enabling fluid movement in open channels driven by pressure. These devices are ideal for scenarios requiring precise control of fluid movement in open channels, such as in high-resolution capillary electrophoresis. They are also adept at manipulating fluids containing suspended particles, such as blood, environmental slurries, multiphase suspensions, and raw biological samples. Moreover, they facilitate the analysis and manipulation of compound mixtures that chromatographically separate in wicking-based devices, and they can handle complex chemical mixtures. Open-channel microfluidic devices hold promise for applications in particle production and methodologies like microfluidic shear separation, which investigate the fluidic-flow characteristics of liquids (46)

Microfluidic paper-based devices offer advantages over devices made of polymers or glass by eliminating the need for valves or pumps, thus simplifying operation and maintaining cost-effectiveness. An optimally integrated paper-based device should be capable of collecting and pre-treating samples, amplifying and transducing signals, and producing results. The analysis would commence upon the entry of the sample, as illustrated in Fig. 1 (47)

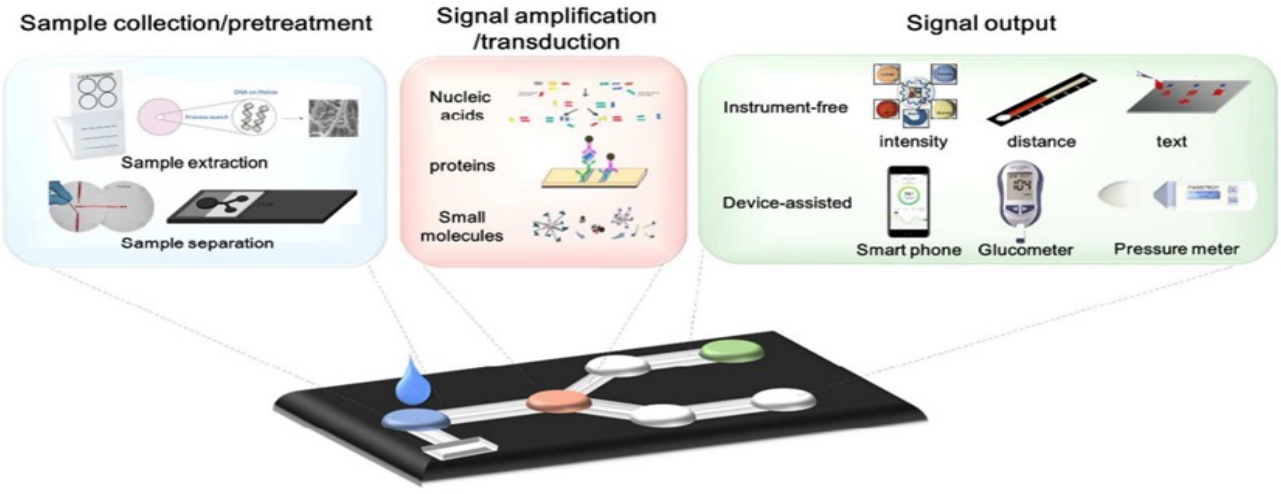

Fig. 1. Overview of an integrated µPAD. An ideal sample-in-answer-out µPAD is expected to include sample collection/pre-treatment, signal amplification/transduction and signal output (47)

Paper is an environmentally sustainable material capable of natural decomposition, compatibility with living organisms, and easily ignitability. Additionally, paper can be incinerated as waste after use. Its flexibility and durability allow for easy customization to meet changing needs. µPADs are widely used across various scientific fields, including food safety, life sciences, and environmental monitoring (48) Clinicians and patients alike require rapid, cost-effective, and user-friendly techniques for disease detection and diagnosis. This is crucial for enabling prompt and efficient treatment, leading to optimal medical outcomes. µPADs are cost-effective and easy to manufacture, making them highly promising for large-scale production. Moreover, their results can be analysed without the need for sophisticated equipment, making them excellent candidates for clinical applications (49).

µPADs play a crucial role in detecting heavy metals in water pollution monitoring. µPADs have been proposed for detecting Hg (II) in various types of water, such as drinking water, pond water, river water, and wastewater. This detection can be achieved through colorimetric or electrogenerated-chemiluminescence (ECL) methods. Additionally, µPADs have been utilised for the quantification of Cu (II) using colorimetric or fluorescence detection techniques. Various parameters, including pH, bacterial classes, chemical substances, and solvents, have also been identified using µPADs by employing suitable colouring reagents or enzymatic reactions (50). The fabrication process of µPADs consists of 2 main steps. Firstly, the paper is patterned, and secondly, the devices are customised for their specific uses, which include the application of reagents for conducting tests. Most patterning processes begin with a computer-generated design of the device, utilising software such as AutoCAD, Clewin, CorelDRAW, Illustrator, and others (51).

The fabrication procedures for µPADs can be classified into 2 main categories: (i) chemical patterning, which involves blocking the pores inside the paper to create barriers, and (ii) physical patterning or cutting, which is used to shape the channels into a specific design. Physical fabrication techniques include knife plotter, craft cutting, embossing and laser cutting (52) Chemical techniques encompass photolithography, wax patterning, wax dipping, inkjet printing, laser treatment and plasma treatment (53). However, these techniques have limitations. For instance, photolithography and wax dipping methods require multiple processing steps, sophisticated and expensive instruments, and are not suitable for mass production. Additionally, there is difficulty in the deposition of biological and chemical reagents in the final form of the test system (54). Recently, there has been significant advancement in connecting these devices to smartphones and various other programs, moving away from traditional detection methods. The development of straightforward, rapid, and cost-effective analytical strategies involving everyday IT communications devices is a notable trend (55).

PDMS microfluidic devices

The initial microfluidic systems were manufactured using glass and silicon wafers as the primary components. However, this process was both time-consuming and expensive, requiring costly equipment and consumables even for producing a single chip. Batch production was significantly more challenging. PDMS provided a cost-efficient platform for microfluidics, offering a competitive advantage (56) Polydimethylsiloxane (PDMS) is a very pliable polymer that can be easily manipulated. It is both affordable and transparent, making it suitable for optical detection systems (57). Additionally, it is biocompatible and easy to mould, allowing for the integration of elastomeric actuators and optical elements into devices. However, PDMS does have some limitations, such as swelling when exposed to organic solvents, the absorption of molecules into the polymer matrix, and its inherent hydrophobic nature. It is also susceptible to elevated temperatures and pressures (58).

Collagen is used to enhance the performance of PDMS microfluidic devices in cell culture applications by acting as a coating reagent. It demonstrate high stability when shear stress. The hypothesis is that the triple helix structure of collagen interacts with receptors on the membranes of vascular endothelial cells (ECs), facilitating cell adherence to the collagen-coated PDMS surface (59).

Furthermore, the production methods for PDMS encounter significant residual deformations, resulting in a misalignment issue where the PDMS patterns are not produced at their intended positions. To address this misalignment, it is crucial to reduce the residual deformations of PDMS by enhancing its strength. Incorporating tougher SU-8 particles, a type of epoxy that acts as a negative photoresist, can improve the strength of PDMS. This incorporation has been shown to decrease the overall residual strain of reinforced PDMS from 5% to 1%, minimizing local distortions and addressing the uneven distribution of SU-8 particles within PDMS (60). As depicted in Fig. 2, the production process begins with the creation of the master mould. This involves applying a layer of negative SU-8 resist onto the substrate via spin coating. The substrate then undergoes a soft (first) bake, which includes a temperature cycle that varies based on the thickness of the SU-8 resist. It is important to avoid high temperatures during the soft bake process to prevent thermal activation before UV exposure (61) The photomask pattern is transferred onto the SU-8 –coated substrate by subjecting it to UV light exposure, followed by a post-exposure bake to accelerate the polymerization of SU-8. The SU-8 is then fabricated to achieve the intended microfluidic structure. The process of PDMS casting on the constructed SU-8 master mould involves creating the PDMS liquid polymer by combining the base elastomer with the curing agent or catalyst. The resulting mixture is poured onto the SU-8 mould and cured using polymeric crosslinking, which can be done either at ambient temperature or at a higher temperature, usually between 40 to 70 °C (62). The most popular technology for fabricating PDMS with microfluidic channel is soft lithography (63) There are also many other technologies, such as wet-etching (64) casting, hot embossing, injection moulding, thermoforming and laser

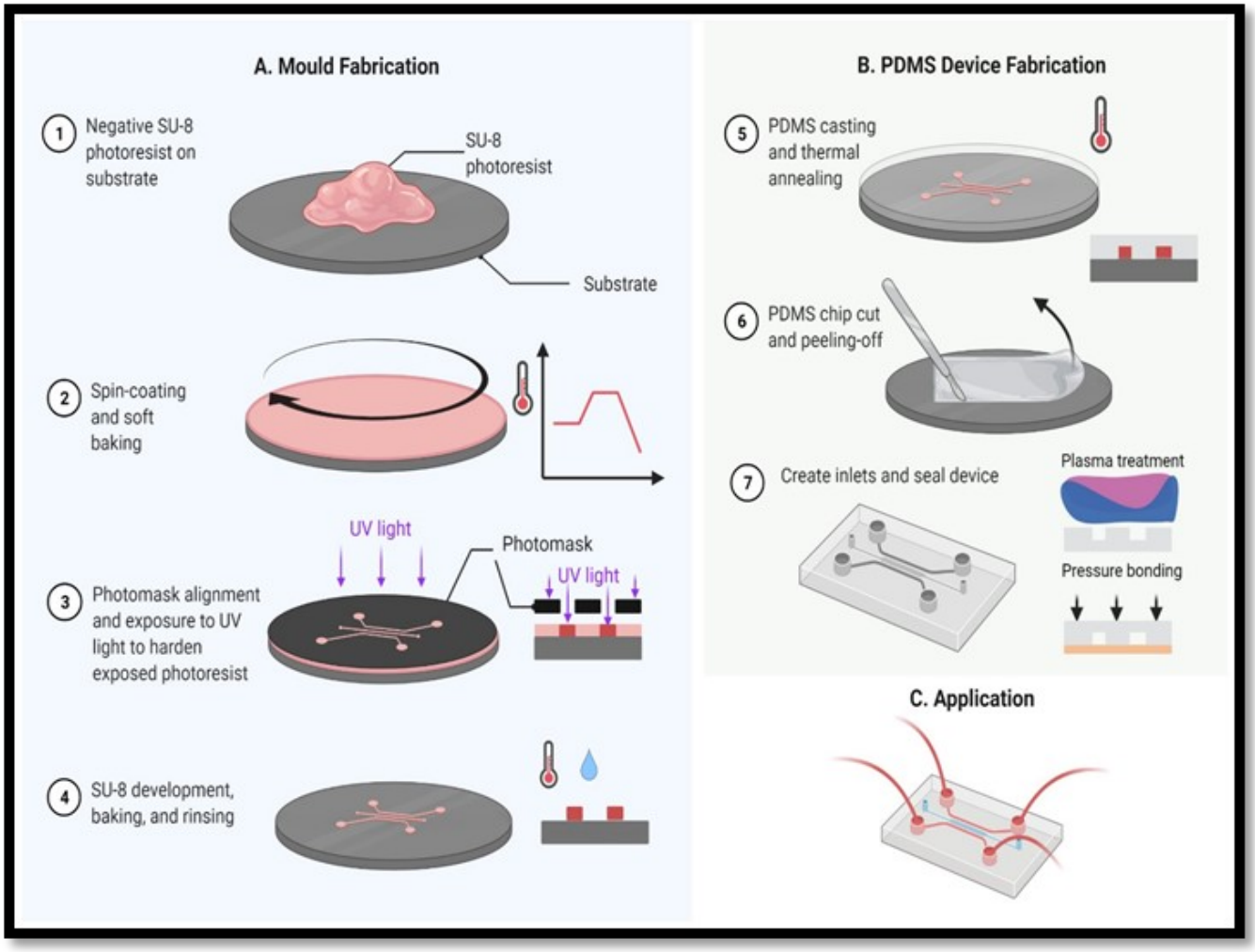

Fig. 2. (A) The process involves making an SU-8 master mould. (B) Then, polydimethylsiloxane (PDMS) is poured onto the mould and treated with plasma. It is then bonded under contact pressure.

ablation (65).

Detection methods

The determination of ionic species, including heavy metal ions and inorganic anions, is of paramount importance in various applications such as diagnosing electrolyte disorder, screening drugs that affect ion channel, tracing trace metals in living organisms, and monitoring air, water, and soil quality. In scientific laboratories, instrumental methods are more suitable for determining the aggregate concentration of individual ions (66) The most popular detection methods used in conjunction with microfluidic devices include:

Optical detection

Optical detection involves observing and identifying characteristics of light, such as fluorescence, absorbance, and luminescence patterns, emitted by materials when they are stimulated. In gas-liquid systems, a potential challenge can arise due to the formation of gas (66).

Fluorescence

Fluorescence intensity measurement is a widely used approach for LOC systems due to its notable sensitivity, selectivity, abundance of fluorophores, and convenient labelling chemistry. Fluorescence is primarily triggered by either laser or LED sources (67) Laser-induced fluorescence is particularly well-suited for microchips because of its adaptability to their dimensions. The coherence and minimal divergence of the laser beam allow for precise focusing on small detection volumes and enable very high irradiation levels, making it an optimal excitation source despite the availability of other options. Consequently, this detection system boasts one of the lowest detection limits among all detection systems. Lamp-based excitation systems offer a cost-effective yet versatile option for selecting the desired wavelength. Microscope-based detector configurations utilizing xenon or mercury lamps have been successfully employed for analysing a wide range of samples, yielding remarkable outcomes (68).

Microfluidic devices have been developed to utilise fluorescence for ion detection, employing various ion-sensing techniques. Fluorescent molecular probes have been designed with a fluorophore as the optical reporter and a recognition unit, such as a chelating structure. Bacterial biosensors have been created to detect heavy metal ions by utilising the ion-regulated production of fluorescent proteins (69).

Various materials have been employed for fluorescence applications. Quantum dots, small particles made of semiconducting material that emit light, have promising applications in biology, including precise labelling of cells and tissues, long-lasting imaging, non-toxicity, *in vivo* imaging using several colours, and fluorescence resonance energy transfer (FRET-based sensing). Fluorescent colours of various hues can be

obtained, depending on the dimensions and configuration of the particles. Additionally, many lanthanide ions offer advantageous properties for bioassays, including extended fluorescence durations, significant differences between excitation and emission wavelengths, and distinct emission patterns. These materials are also used for studying the quality and effectiveness of food (70) Furthermore, it is possible to attach fluorophores to the surface of paper. Smartphones, equipped with advanced sensors, high-resolution cameras, and powerful computing capabilities, have been employed as compact and portable analytical instruments. In fluorescence measurements, they capture fluorescent reactions and quantify tests in various fields when integrated with µPADs (71).

Absorbance

UV/visible absorption spectroscopy is a widely used method in large-scale analytical chemistry and laboratory diagnostics. This technique involves measuring the decrease in intensity of incoming light at different wavelengths using a spectrophotometer. The resulting spectrum displays absorption peaks, which can be used to determine the composition and concentration of the sample (72). Absorption spectroscopy continues to be a highly effective and extensively utilised technique for evaluating cellular dynamics in microfluidic experiments. Optical absorption spectra can be used to determine different cellular behaviours by analysing how analytes and products affect them (73).

Microfluidic devices can utilise a range of optical micro-components that effectively concentrate and direct light to a specific location, resulting in a highly sensitive and long-lasting detection process at a low cost. Many efforts have been made to create novel optical prisms, lenses, and waveguides to integrate lab-on-a-chip technology (74).

This reduction in path length directly affects the sensitivity of the detection, as explained by the Beer-Lambert equation. Although microfluidic absorbance detection has lower sensitivity compared to fluorescence (75)

Chemiluminescence

Chemiluminescence (CL) is a form of electromagnetic radiation that occurs when a molecule is excited to the singlet excited state through an exothermic chemical process. When the molecule returns to its ground state, it emits a photon with a specific wavelength, primarily in the visible and near-infrared regions. By measuring the intensity of the emitted light, one can conveniently correlate this intensity to the concentration of the analyte (76) CL detection offers excellent sensitivity and selectivity with minimalistic apparatus for signal gathering. Since the radiation is produced by chemical reactions, there is no need for light sources to carry out measurements. As a result, only photo transducers are used in the detector. This makes CL a viable option for microfluidic analytical devices, as it effectively manipulates external light beams within narrow chip channels (77) Several studies underscore the significance of CL approaches in analytical chemistry. These methods are utilized for the determination of a wide range of chemicals, including medicines, biomolecules, antioxidants, pesticides, arsenates, and environmental water (78) The detection principles of CL in immunoassays involve using an enzymatic-label conjugate with an immunoreagent and a specific bioluminescence (BL) or CLsubstrate. By employing BL or CL, a significant enhancement in the analytical signal (approximately 10^4-10^5 times) can be achieved compared to the typical enzymatic turnover (79).

While microfluidic devices using CL detection are becoming more sophisticated and larger compared to those using UV/vis and fluorescence detection, they are essential for accurately measuring the optimal emission intensity produced by slow CL reactions like luminol peroxyoxalate. These devices necessitate long response channels and wide detection windows. However, adding extra flow components to measure CL does not enhance resolution due to broad band-broadening. Moreover, detecting slow and relatively dim CL using micro-scale detection windows poses significant challenges (80).

Electrochemical

Electrochemical sensors function based on the fundamental principle that chemical reactions between the immobilized synthetic recognition element and the target analyte either produce or consume ions or electrons (81). The primary advantage of microfluidic techniques lies in their portability and user-friendly nature, rather than their sensitivity(82)

These techniques utilize an analyte solution containing the target species for quantification. The effectiveness of the method is assessed based on sensitivity, which denotes its capability to detect low concentrations and the minimum concentration that can be reliably measured, and selectivity, which refers to its ability to differentiate the target species from other substances in the solution (83). The challenge lies in fabricating miniaturized electrochemical systems, as they require integrating thick electrodes within microfluidic microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) (84).

There are many applications for electrochemical sensors for instance Paper microfluidic electrochemical device target blood ions (Cl^{-1}, Na^{+1}, K+, and Ca^{+2}) with limit of detection (-47.71, 45.97, 51.06, and 19.46 in mV decade $^{-1}$) respectively (85),and there is a paper-based microfluidic e integrated screen-printed carbon electrodes (SPCE) used for detection of Pb (II) and Cd (II) in aqueous samples with limit of detection (2.0 and 2.3 ppb), respectively (86).

Another application uses microfluidic paper-based to detect Pb (II)) in urine samples in limit about 9 µg L^{-1} (87). In addition, using PDMS microfluidic devices for detection of a cell types (dhesion of murine 3T3 fibroblast cells) about 24 cells (88). And using microfluidic channel made from (poly dimethylsiloxane) (PDMS) to detect H_2O_2 with limit of detection about 5 nM (89)

While Electrochemical double-layer capillary capacitors (µEDLC) in polydimethylsiloxane (PDMS) substrate target breast cancer biomarker (CA 15-3) and limit of

detection 92.0 µU mL^{-1} (90)

Novel methods

Recently, several novel detection techniques have emerged that reduce costs, increase sensitivity, improve ease of use, and expand possibilities. Among these, nanosensors and quantum dots (QDs) stand out, particularly in their integration with cell phones as self-contained microfluidic devices. This section will focus on these 2 techniques to provide a comprehensive overview of their applications.

QDs are nanocrystals made from semiconducting materials, typically ranging in size from 2 to 10 nm. Their unique optical and electrical properties stem from quantum confinement effects, which differ significantly from those of larger bulk materials (91) Graphene quantum dots (GQDs), a type of carbon-based quantum dot, can be combined with other materials to form nanocomposites with exceptional characteristics and enhanced performance. Consequently, GQDs are considered promising composite materials suitable for applications in agriculture and environmental sciences (92). In general, there exists a correlation between the concentration of heavy metal ions and the enhancement of quantum dot (QD) fluorescence intensity, making it feasible to detect heavy metal ions using QDs (93)

The researchers have introduced an integrated microdevice with a solid-phase extraction (SPE)-graphene oxide quantum dot (GOQD) array for detecting trace heavy metals such as As^{3+}, Cd^{2+}, and Pb^{2+}. This device selectively separates metal ions from raw aqueous samples using on-chip SPE. The separated ions are then quantitatively analyzed using a DNA aptamer-linked GOQD array sensor. The detection limits for As^{3+}, Cd^{2+}, and Pb^{2+} were found to be 5.03 nM, 41.1 nM, and 4.44 nM, respectively. The device successfully achieved simultaneous detection of As^{3+}, Cd^{2+}, and Pb^{2+} in ambient samples on a miniature scale (94) Additionally, GQDs have been employed to enhance microfluidic gas sensors . GQDs were utilized to create nanoscale structures on microchannel walls. These modified sensors were exposed to seven different analytes at 100 parts per million (ppm) concentrations (methanol, ethanol, propanol, pentanol, hexane, hexanal, and toluene). The sensors' responses to these analytes were measured, analyzed, and compared with those of unmodified sensors. The methods demonstrated significant improvements in sensor selectivity, showcasing a proof-of-concept for enhancing selectivity through enhanced surface adsorption/desorption effects compared to mass diffusion in microfluidic gas sensors (95)

Conventional microfluidic systems traditionally rely on bulky external equipment like pumps, centrifuges, and microscopes to control flow, prepare samples, and monitor processes. These systems are typically confined to clinical or laboratory settings due to their dependence on external components. Hence, there is a pressing need to advance microfluidic devices (96) Considering the ubiquity of smartphones-portable, user-friendly, and equipped with numerous applications (97) it becomes imperative to explore integrating these devices into microfluidics for broader accessibility and enhanced functionality.

Smartphones are emerging as versatile tools for alternative detection devices in microfluidic applications. For example, smartphones are utilized in digital microscopy and flow cytometry, leveraging their cameras for the examination of biological specimens such as cells, bacteria, and parasites at the point-of-care (POC) (98) The researchers have demonstrated a paper-based microfluidic colorimetric sensor capable of simultaneously determining pH and nitrite concentration in water samples (99). Additionally, some researchers have introduced the micro capillary film (MCF) phone, a flexible smartphone-based system for colorimetric and fluorescence detection, successfully detecting prostate-specific antigen (PSA) from whole blood within 13 min using colorimetric methods and 22 min using fluorescence detection (100). These advancements suggest that in the near future, smartphones could enable a wide range of analyses for various samples, whether in clinical or environmental contexts, driven by ongoing research efforts to develop microfluidic devices tailored to environmental applications.

Conclusion

This study presents microfluidic devices as highly selective and sensitive tool for detecting water pollution, offering advantages over traditional methods. These devices streamline laboratory work to a single chip, enabling fast, cost-effective, and on-site detection. Future work should focus on enhancing the accuracy of these devices through improved design, selecting analytical methods that yield high-quality results, and integrating them with smartphones applications to provide the most precise outcomes.

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Authors' contributions

RKM contributed to the authorship and writing. DSZ was involved in authorship and writing. KAK was responsible for planning and writing.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

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