

# Recent Advances in the Application of Microfluidic Paper Based Devices for Environment Sample Analysis

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## ABSTRACT

High demand for the development of very simple, low-cost, portable, environmental friendly and user-friendly detection approaches, particularly in developing countries and remote areas with a lack of sufficient infrastructure, professional experts, and appropriate environmental treatment. Microfluidic paper-based analytical devices ( $\mu$ -PADs) have a tremendous potential to fill this gap since such devices are simple, low-cost, rapid, portable and are highly demanded in developing countries. This review recaps the recent progress of paper-based analytical devices and discusses the advantages of paper substrates. Some of the important device fabrication and detection methods also relevant theories regarding environmental monitoring issues are described with examples in detail. Efforts have been made to explore the role of nanostructured materials to enhance the performance of paper-based microfluidic devices. We have analyzed the recent reports on the development of these devices for recognition of environmental issues employing different methods. Further, the future development and trend in this field are discussed.

**Keywords:** Microfluidic; Paper-Based Devices; Fabrication; Environmental Monitoring

**Abbreviations:** GC: Gas Chromatography; HPLC: High-Performance Liquid Chromatography; EDXRF: Electrochemical Methods, Energy Dispersive X-Ray Fluorescence; ICP-AES/OES: Inductively Coupled Plasma-Atomic/Optical Emission Spectrometry; FAAS: Flame Atomic Absorption Spectrometry; EC: Electrochemical; ECL: Electro Chemiluminescence; PEC: Photo Electrochemistry; SERS: Raman Scattering; HCG: Human Chorionic Gonadotropin; TMDs: Transition Metal Dichalcogenides

## Introduction

Continuous industrialization and technological development have significantly contaminated the air, land, and water in many parts of the world. These pollutants frequently include elements like nitrogen, phosphorus, and carbon along with a variety of other contaminants like organic pollutants, heavy metals, drugs, herbicides, insecticides, disinfectants, and industrial byproducts. This pollution not only endangers the environment and its surrounding ecosystems but also puts human health and economic progress at serious risk (Kung, et al. 2019). For sustainable development, pollution is a persistent and serious problem in many Sub-Saharan African nations. Pollution abatement may be neglected in the face of investor pressure to support industrial activities, even in the presence of environmental regulatory

frameworks. A vicious cycle of “pollute now, clean up later” can result from policies designed to maximise economic gains. The apparent conundrum of creating sound environmental regulations but not enforcing them runs the risk of making industrial growth unsustainable (Sikder, et al. (2013)). In addition, a lot of industrial technologies are fairly outdated, and in an effort to comply with environmental regulations while facing mounting economic pressure, there is a propensity to import less expensive technologies.

The environmental Kuznets curve indicates that until technology reaches the scrapping age, operational costs will not be able to cover the market value for environmental quality (Bertinelli, et al. [1]). At that point, the ratio of socioeconomic development to pollution may rise. A list of specifications for the development of point-of-care di-

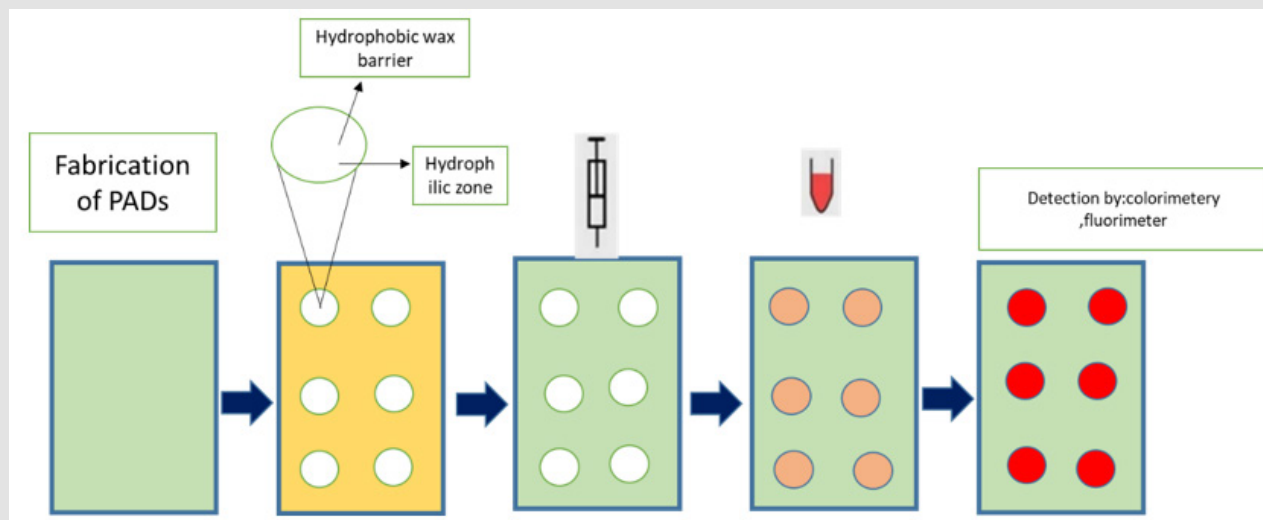
agnostic devices in low-resource settings has been developed by the World Health Organization. The acronym “ASSURED” refers to these specifications, which include being robust, sensitive, fast, accurate, and user-friendly. For all these purposes, a rapidly emerging technology called microfluidics can be employed. Fluids with volumes ranging from microlitres to femtolitres are the subject of microfluidics, which deals with objects or systems with dimensions less than a millimetre (Banerjee [2]). The development of point-of-care (POC) testing platforms to supplement traditional (bio)chemical assays is highly pursued, as it provides new opportunities for rapid, portable, low-cost, and real-time investigations. POC platforms also make on-site testing possible and do away with the need for big, costly benchtop instruments, which usually call for skilled operators.

This makes monitoring water, food, and environmental safety, as well as healthcare, accessible and affordable for nations with limited resources (Rahbar [3]). These days, “ $\mu$ PADs were very popular due to their low expenditure, simplicity, adaptability, and disposability,” assert De Oliveira, et al. (2017). An analytical device can react to a patient test sample in a timely and financially advantageous manner.  $\mu$ PADs can be made with a simple, compact, handheld, and portable tool (Nurul, et al. 2019). According to (Whitesides, 2006) in his article published in Nature in 2006, microfluidics is the science and technology of systems that handle and manipulate small volumes of fluid using fluidic channels with dimensions ranging from tens to hundreds of micrometres. Microfluidics has grown quickly and had a noticeable impact on the analytical chemistry community because of a number of capabilities, such as the ability to perform separation and detection with high sensitivity and resolution at low cost and speed, using small

amounts of samples and reagents, and more. Early works on the development of microfluidic devices discussed the use of polymers such as poly (dimethylsiloxane) (PDMS), glass, and silicon as substrates.

Even though these devices reduce the size of traditional techniques for distinct target separation and detection Mentele, et al. (2012) state that paper’s abundance, low cost, disposable nature, ease of use, portability, and storage, along with its large visual surface area and chemical changeability, make it a desirable substrate for microfluidic devices. Paper has generated a lot of interest in the microfluidic device for the following reasons:

- 1) It is a cheap, easily accessible cellulosic material.
- 2) It is ideally suited for numerous chemical, biochemical, and medical applications; and
- 3) It transports liquids using capillary forces without the need for outside forces. Liquid flow can be controlled by creating microfluidic channels on paper because the flow is contained within the channels (Li, et al. [4]). (Figure 1) illustrates a typical setup for an analytical device based on microfluidic paper. This is a typical configuration for a microfluidic analytical device based on paper:
  - a) Unmade Whatman filter paper.
  - b) A  $\mu$ PAD with clearly defined hydrophobic barriers and hydrophilic zones.
  - c) Reacting reagents pre-loaded.
  - d) Sample loaded onto the  $\mu$ PAD; and
  - e) Colour development.



**Figure 1:** An Example of Microfluidic paper based analytical device.

The properties mentioned above are present in microfluidic paper-based analytical devices ( $\mu$ PADs), which are acknowledged as a potentially potent analytical platform. For analytical purposes, paper offers a number of benefits. Specifically, it can be easily designed into distinct hydrophilic and hydrophobic zones using current printing or cutting techniques, and it is cheap and widely available. It can wick fluids through capillary action as well, eliminating the need for outside power sources. It is lightweight, disposable, and biodegradable. Determining the toxins or heavy metals responsible for soil and water pollution is the main objective of environmental monitoring. To detect mercury (II) ions, gold nanoparticles immobilized with single-stranded DNA (ssDNA) on the surface are spread on paper microfluidics. If mercury (II) ions are present in the sample, the ssDNA forms Thymine-Hg<sup>2+</sup> Thymine bonds and loses its affinity for the nanoparticle surfaces. At the moment, aggregation occurs between nanoparticles on the surface that lack ssDNA, and the color changes depending on the degree of aggregation. The concentration of mercury (II) ions is calculated by examining the degree of color change. This review is briefing the significance of the  $\mu$ PADs on the environmental monitoring. Also, we described microfluidic paper-based analytical devices and different fabrication and detection techniques.

We have also covered the environmental applications of  $\mu$ PADs with examples from previously reported works, the role of nanomaterial in the microfluidic paper-based analytical devices and various breakthroughs in this field (Chen, et al. [5]). However much of the research up to now has been on the biomedical advantages of  $\mu$ PADs. there has been little discussion about environmental applications of  $\mu$ PADs. this review critically examines an account of analyzing literatures conducted on environmental applications of  $\mu$ PADs. The review also provided an important opportunity to advance the understanding of  $\mu$ PADs environmental applications and it aims to conduct to this growing area of research by exploring literatures.

### Fundamentals of Paper-based Microfluidic Analytical Devices

Hydrophobic boundaries offer a physical barrier that keeps samples from dispersing in hydrophilic zones.  $\mu$ PADs function in this way. Each  $\mu$ PAD is built with multiple detection zones coated with the appropriate organic sensors in order to identify the target hazardous ions. For multiple simultaneous analyses, the solutions travel in a passive capillary manner through a pattern of filter sheets to reach the zone of detection. Because the analyte interacts with an organic receptor at the detecting zone to cause a rapid colour change, the device is flexible. As a result of the reaction with preloaded reagents,

the yellow colour dye in  $\mu$ PADs functions as a capillary and rapidly changes colour in the detecting zone (Sriram, et al. [6]).

### General Aspects of $\mu$ PADs

(Arya, 2014) states that the manipulation of fluids at the microscopic level is the main focus of the field of microfluidics. Sackmann, et al. (2014) claim that because turbulent flows allow for more efficient transport phenomena, conventional macro-scaled operations are commonly carried out in these conditions. The forces of gravity and fluid inertia are overcome by narrowing the channel diameters. Busa, et al. (2016) and Lin, et al. (2016) state that surface tension, viscosity, and fluid density become important considerations. The hydrophilic fibres have excellent contact with aqueous samples, which means a low energetic cost when compared to plastic materials because capillarity can be used as a driving force for fluids and pumps or other devices are not always necessary (Cate, et al. [7]). Thanks to developments in microtechnology, "labs-on-a-chip," or laboratories placed on a micro-device, are now feasible (M Dou, et al., 2014). Portability is one of the most important features of  $\mu$ PADs. Eliminating the need to transport samples to the lab lowers the risk of contamination or deterioration and eliminates the need for sample preservation. According to Almeida, et al. [8], on-site analysis therefore enables a quicker turnaround time for results at a lower cost of analysis.

### Applications of $\mu$ -PADs

PADs have been acknowledged as a significant advancement in portable and reasonably priced POCT diagnostics. Over the past ten years, these devices have changed because fewer analytical steps are now required, and they are flexible paper-based devices that provide fast results. This promising replacement for conventional microfluidic devices has made possible a wide range of fluidic applications, such as drug diagnosis, environmental monitoring and pH monitoring, food safety and water analysis, heavy metal ion detection, cancer diagnosis, toxic and poisonous materials detection, and explosives analysis (Selvakumar, et al. [9]). According to (Barocio, et al. [10]), these microsystems have the following benefits over traditional laboratory equipment: smaller sample requirements, faster reaction times, and portability. There are many possible applications for these kinds of microsystems, ranging from environmental to medical. Microfluidic devices can identify and measure a wide range of contaminants when they are used in conjunction with suitable assays and extremely sensitive detection methods. (Figure 2) is a schematic design that illustrates the benefits and drawbacks of paper-based analytical tools as well as potential ways to increase sensitivity.

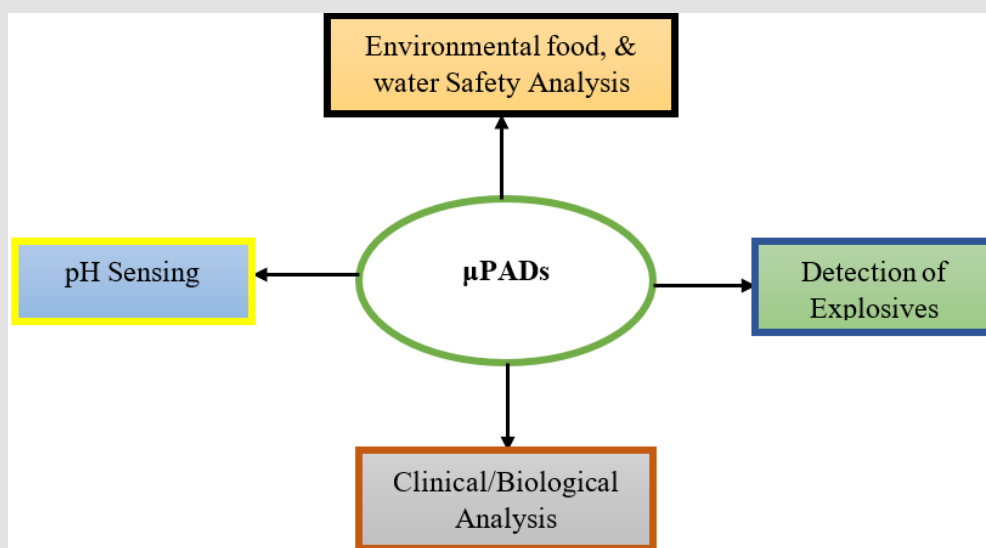


Figure 2: Applications of  $\mu$ PADs in different analysis.

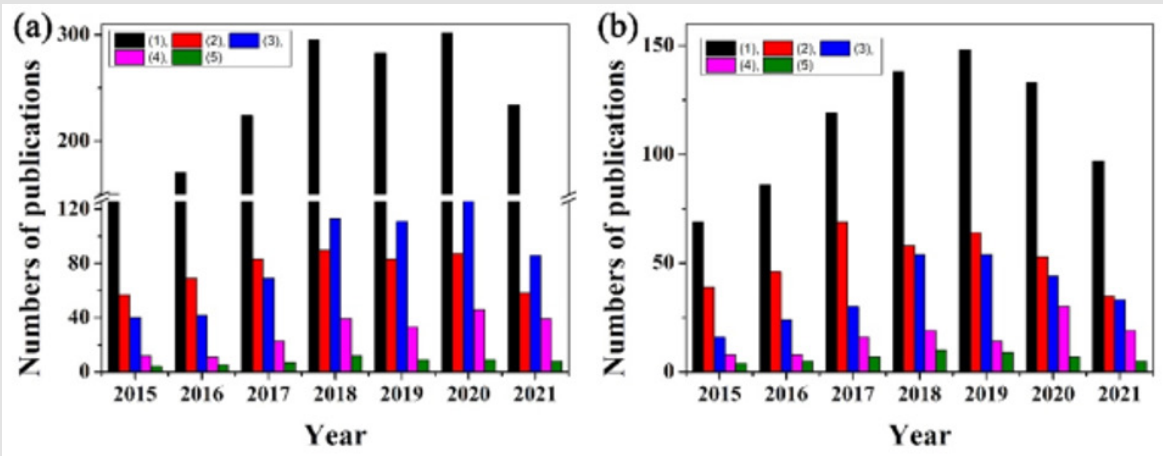
### Advantages of $\mu$ PADs Compared to Conventional Methods for Expanding Environmental Monitoring

**Conventional Approaches:** Numerous traditional methods are available for the detection of hazardous chemicals in environmental assessments, including pesticides, heavy metals, microbes, nutrients, and organic pollutants. The methods used in these investigations include gas chromatography (GC), high-performance liquid chromatography (HPLC), electrochemical methods, energy dispersive X-ray fluorescence (EDXRF), energy dispersive plasma mass spectrometry (ICP-MS), inductively coupled plasma-atomic/optical emission spectrometry (ICP-AES/OES), and flame atomic absorption spectrometry (FAAS). But it takes a lot of time to operate, expensive, heavy equipment, and skilled labour. Because of this, scientists have been working to develop detection technologies that are inexpensive, straightforward, sensitive, exact, accurate, user-friendly, and environmentally safe.  $\mu$ PADs are among the most promising solutions (Lin, et al., 2016).

**Microfluidics for Environmental Remediation:** Growing economies are putting the environment at risk because of the excessive release of hazardous industrial byproducts into the environment. It gets harder and harder to manage the enormous amounts of waste that are released into the atmosphere and water bodies as a result of industrialisation and urbanisation, which increases the demand for clean resources. Alternatives that are more economical and efficient are highly sought after since traditional cleanup techniques fall short of regulatory effluent limitations. Numerous factors, such as waste type and concentration, the amount of cleanup required, and post-processing technology, influence the choice of treatment technique for both water and air discharge (Jiang, et al. [11]). In general, these

techniques have outstanding precision, strong specificity, and high sensitivity. Surface enhancement, fluorescence, and colorimetry In addition to electrochemical (EC) methods like amperometry, potentiometry, voltammetry, electrochemical impedance spectroscopy (EIS), electro chemiluminescence (ECL), and photo electrochemistry (PEC), Raman scattering (SERS) and other optical techniques are used to detect  $\mu$ PADs (Fu, et al. [12]).

The most straightforward and useful of these detection methods is colorimetry, which was the main method used in  $\mu$ PADs until 2009. The main advantage of paper-based colorimetric devices is that they don't require expensive or complex equipment to quickly and easily detect the presence of a specific analyte based on a colour shift. However, a number of intrinsic limitations of the colorimetric method, such as a limited dynamic range, low sensitivity, easy interference from ambient light, and subjective bias from users, limit it to qualitative yes/no detections and/or semi-quantitative analysis. In general, electrochemical paper-based analytical devices, or ePADs, perform better in terms of sensitivity and accuracy than paper-based colorimetric analytical devices. Regrettably, complex matrices have the potential to significantly impair ePADs' analytical performance, especially their selectivity. EC detection and optical detection are currently the two main methods used to detect  $\mu$ PADs (Ding, et al. 2021) (as shown in Figure 3). In order to overcome these limitations, nanomaterials were utilised to provide sensitive and selective detection signals on  $\mu$ PADs, given that they and their composites exhibit unique physical and chemical properties (Quesada-González, et al. 2015). For example, gold nanoparticles (AuNPs) and magnetic nanoparticles (MNPs) have been used extensively as signal indicators for colorimetric analytical instruments that are based on paper (Patel, et al. [13]).



**Figure 3:** Annual publication numbers on PADs from 1 January 2015 to 30 October 2021.  
a) (1) paper-based analytical devices (2) electrochemical (3) colorimetric (4) fluorescence (5) raman and  
b) (1) paper-based analytical devices plus nano- particle/nanoparticles and paper-based analytical devices plus nanoparticle or nanomaterial plus (2) electrochemical, (3) colorimetric, (4) fluorescence (5) Raman.

Several AuNPs labelled lateral-flow test-strip (LFTS) immuno-sensors, such as the colloidal gold immunoassay strips for hepatitis B surface antigen (HBsAg) and human chorionic gonadotropin (HCG), have been clinically approved for rapid testing. Transition metal dichalcogenides (TMDs) and carbon nanomaterials, like graphene and carbon nanotubes, can be used as functional materials on electrode surfaces to improve the sensitivities of ePADs by increasing actual electrode area and accelerating electron transfer (Solhi, et al. [14]). The phenomenon further improves the 'PAD's sensing capabilities. Consequently, the incorporation of nanomaterials into PADs expands their applicability and improves their quantitative capabilities (Pang, et al. [15]). At the moment, a lot of work is being done to employ

novel materials, specifically nanomaterials and their composites, to increase the  $\mu$ PADs' capacity for detection (Solhi, et al. [14]). Solhi [14] discusses the use of electrochemical (EC) techniques such as amperometry, potentiometry, voltammetry, electrochemical impedance spectroscopy (EIS), and photo electrochemistry (PEC) in addition to colorimetry, surface enhancement Raman scattering (SERS), fluorescence, and other optical techniques to detect PADs. Up until 2009, colorimetry was one of the main detection methods in  $\mu$ PADs. It is one of these simple and useful detection methods. Table 1 compares and summarises the benefits and drawbacks of the four primary  $\mu$ PADs detection methods (EC, Colorimetric, Fluorometric, and SERS  $\mu$ PADs).

**Table 1:** The comparison of four representative detection methods of  $\mu$ PADs.

| Detection Methods       | The Main Nanomaterials                                                        | Advantages                                                                                      | Disadvantages                                                                      | Limit of Detection                                      |
|-------------------------|-------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|---------------------------------------------------------|
| EC $\mu$ PADs           | AuNPs, graphene, MOF, multiple metallic NPs composites and functionalized NPs | High sensitivity, rapid response and easy miniaturization                                       | Equipment- dependent, complicated operation, easy interfered with complex matrices | 1 pg mL <sup>-1</sup> level for AuNPs,                  |
| Colorimetric $\mu$ PADs | Functionalized AuNPs and AgNPs, enzyme-like nanomaterials                     | simplicity, ease of use, naked-eye reading, speed, affordability, and little sample consumption | Poor sensitivity, limited to qualitative or semi- quantitative analysis            | 10 pg m L <sup>-1</sup> level for functionalized AuNPs, |
| Fluorometric $\mu$ PADs | NC, QD, CD, MOF                                                               | Low cost, easy operation                                                                        | Reader- dependent                                                                  | 10 pg m L <sup>-1</sup> level for MOF                   |
| SERS $\mu$ PADs         | AuNPs and AgNPs                                                               | On-site label-free detection, offered fingerprint signatures, high sensitivity                  | Equipment dependent                                                                | 1 pg m L <sup>-1</sup> level for AuNPs                  |

## μPADs Environmental Applications in Different Areas

Paper-based methods are attractive because they enable quick, low-cost, on-site detection of contaminants and can also be used as preventive measures for antioxidants, heavy metals, food additives, air, soil, and water contamination, explosives, quality control issues, pathogens, and insecticides. Environmental pollution has gained international attention as a result of the increase in human activity. Industrialisation has contributed significantly to economic growth, but the trade-off between environmental conservation and the release of pollutants and toxic wastes into ecosystems has had unfavourable effects. From straightforward separation methods to sophisticated remediation technologies, a variety of detection, monitoring, and clean-up technologies have since been developed. According to Jokerst, et al. (2012), there are still significant obstacles in the form of the detection limit and cost of currently available technologies, even though certain pollutants can be readily captured and retained after established work on a macro- or industrial scale. Beyond laboratory-on-a-chip and natural and biological science applications, microfluidic systems have advanced. The use of microfluidic technologies for environmental detection is becoming more popular due to their cutting-edge accuracy, promptness, and affordability. Yew and colleagues, 2019.

### Microdevices for Monitoring and Detection of Pollutants

Portable sampling devices are emerging in the form of miniaturised analytical equipment and microdevices with fluidic channels. The development of portable electrochemical instruments A portion of pollutant sampling has been done using sensors and biosensors. overcome challenges with laboratory-based analyses, like lengthy preparation times and sample quality changes beforehand, while LOC sensors integrated multiple traditional procedures into a single system. One of the smaller characteristics of microfluidic systems is rapid response, which has several advantages. Low sample and reagent demand, real-time characterisation, and analysis In addition, a portable microdevice might have sample flow channels, an on-chip pretreatment section, and a miniature detector that can be connected to the analytical unit of a full-fledged laboratory (Walker, et al. [16]).

**Water Quality:** Ensuring safe health through water quality monitoring is of utmost importance. MEMS-based microfluidic devices are employed in environmental monitoring. Examples of common sensors are a resistive temperature sensor, a piezoelectric pressure sensor for depth measurement, and a conductivity cell based on liquid crystalline polymer (LCP). When assessing the quality of water in a harsh environment, MEMS-based microfluidic devices filled with polystyrene and epoxy are particularly helpful. Nevertheless, the relative error is less than 8% in comparison to the reference biosensor after five days. Ensuring safe health through water quality monitoring is of utmost importance. MEMS-based microfluidic devices are employed in environmental monitoring. Examples of common sensors

are a resistive temperature sensor, a piezoelectric pressure sensor for depth measurement, and a conductivity cell based on liquid crystalline polymer (LCP). Polystyrene and epoxy-filled MEMS-based microfluidic devices are helpful for assessing the quality of water in challenging conditions (Saxenaa [17]).

Nevertheless, the relative error is less than 8% in comparison to the reference biosensor after five days. Ensuring safe health through water quality monitoring is of utmost importance. MEMS-based microfluidic devices are employed in environmental monitoring. Examples of common sensors are a resistive temperature sensor, a piezoelectric pressure sensor for depth measurement, and a conductivity cell based on liquid crystalline polymer (LCP). Centrifugal microfluidics are another kind of colorimetric microfluidic device that is used; they are capable of simultaneously detecting nitrite, nitrate, ammonium, orthophosphate, and silicate in water samples. It is a revolving disc-shaped device that needs only 10–30 L of reagent and 500 L of sample. The ferrowax-based microvalves in this device are exposed to laser radiation, which regulates the fluid transfer. A laser diode is used to program the time as the sample and reagents are pumped into the rotating discs in liquid form (Hwang, et al. [18]). An integrated microfluidic device called a Microchip Capillary Electrophoresis (MCE) system can identify perchlorate concentrations in drinking water as low as 15 parts per billion (ppb). This system's advantages include the assay's sensitivity and quick detection. It's a portable instrument that doesn't need much sample preparation. Nhexadecyl-N,Ndimethyl-3-ammonio-1-propane sulfonate (HDAPS) and N-tetradecyl-N,Ndimethyl-3-ammonio-1-propane sulfonate (TDAPS), two zwitter ionic, sulfobetaine surfactants, are responsible for this device's high resolution (Gertsch, et al. [19]).

**For Detection of Heavy Metals in Water Samples:** It is currently established that human exposure to metals increases the risk of disease and death, especially in regions with weak regulations pertaining to water pollution by metals. Even though exposure to metals is associated with a number of diseases, determining the precise source of metal exposure is challenging due to the expense of measurement. Since 2010, coloured metal-ligand complexes have brought attention to metal quantification with paper-based sensors by being observable with the unaided eye and/or being reasonably quantifiable with other optical modalities, like a scanner or camera-phone (Meredith, et al. [20]). (Shi, et al. [21]) used square wave anodic stripping voltammetry (SWASV) to develop an electrochemical μPAD for Pb (II) and Cd (II) detection. The development of a microfluidic device for the detection of Pb (II) and Cd (II) in aqueous samples made use of screen-printed carbon electrodes (SPCE) and filter paper strips. Several analytes in contaminated aqueous samples were directly measured for Pb (II) and Cd (II) using a portable microfluidic system (with direct electrochemical detection). Commercial salty soda water and dirty ground water were used as model samples for Pb (II) and Cd (II) detection in the study.

The Square Wave Anodic Stripping Voltammetric (SWASV) signal has been shown to have good analytical performance for Pb (II) and Cd (II) detection (from 0 to 100 ppb), with low limits of detection of 2.0 and 2.3 ppb, respectively, according to Jianjun Shi's analysis. The selectivity and stability of these devices were also demonstrated when they were utilised to analyse real samples of gas-dissolved salty soda water, physically contaminated ground water, and electrochemical  $\mu$ PADs devices. The tool is easy to make, portable, affordable, and basic in design. Exposure to mercury can have detrimental effects on human health as well as the environment due to its extreme danger. Mercury pollution in the environment can be caused by a variety of factors, including metal mining, industrial waste, bleach manufacturing, agricultural pesticides, and volcanic activity. Because mercury (II) is soluble in water, it can contaminate vast amounts of water, making it one of the most common and stable forms of mercury pollution (UNEP, 2002). Hg (II) buildup in these vital organs via the food chain can cause major harm to the brain, neurological system, kidneys, heart, and endocrine system (Gu, et al. 2011). Thus, it is essential to continuously check the Hg (II) ion levels in the environment. Because mercury is so toxic, the US Environmental Protection Agency (USEPA) limits its presence in drinking water to 0.002 mg/L (Smeenk [22]).

Two real water samples were used to evaluate the AgNPLs/Cu (II) device that was proposed in a paper by Apilux, et al. [23]. One sample came from commercially bottled drinking water, and the other from tap water at home. AgNPLs was utilised to develop a colorimetric method for Hg (II) ion concentration measurement. The hue transitioned from pinkish violet to pinkish yellow upon the identification of the Hg (II) ion. The observed phenomenon can be accounted for by a change in the surface plasmon resonance of AgNPLs, which is related to the AgNPL's apparent hue and colour. As one can see with their own eyes, the colour of the AgNPLs begins to fade when Hg (II) concentrations rise above 25 ppm. However, the system's quantitative performance was improved with the aid of digital imaging and software processing, and effective applications to real sample analyses of tap and drinking water revealed a detection limit of 0.12 ppm. The analytical recoveries for the tap and bottled water, respectively, were within acceptable ranges of 90-113% and 96-103% when these water samples were spiked with different concentrations of Hg(II).

The precisions (% RSD) revealed ranges of 3.3-8.6% and 3.2-4.9%, respectively (Table 2). The two water samples' Hg(II) levels are most likely less than 2 ppb, and the agreement between the detected and predicted values suggests that their matrices haven't masked them. These findings validate the employed detection method and demonstrate the effectiveness of the method developed here for the detection of Hg (II) in real water samples. Compared to the other metal ions examined, paper-AgNPLs/Cu (II) more favourably selects for Hg(II). The findings also show that the analytical signal for Hg (II) is

greatly increased when Cu (II) is added to the Ag Nanoplates at the test zone. When digital camera imaging and software processing are used, the linear detection range is 5-75 ppm Hg (II) with a limit of detection of 0.12 ppm, which is demonstrated to greatly increase the quantitative capabilities of this technology. Using a pre-concentration method (based on multiple 2 mL administrations of the test Hg (II) solution over the same test zone), the limit of detection is lowered to 2 ppb. The technology used in this work provides a rapid, sensitive, and targeted approach for detecting aqueous Hg (II) samples, and is especially well-suited for remote field and environmental analysis.

**Table 2:** Determination of Hg (II) levels in real water samples.

| Sample         | Hg (II) (ppm) |            | % Recovery | % RSD |
|----------------|---------------|------------|------------|-------|
|                | Added         | Found      |            |       |
| Drinking water | 0             | ND         | -          | -     |
|                | 1             | 1.0370.24  | 103        | 4.94  |
|                | 5             | 4.7870.27  | 96         | 3.57  |
|                | 10            | 9.6070.32  | 96         | 3.2   |
|                | 25            | 24.7170.33 | 99         | 3.24  |
| Tap water      | 0             | ND         | -          | -     |
|                | 1             | 0.8970.40  | 90         | 8.53  |
|                | 5             | 4.5770.29  | 91         | 5.1   |
|                | 10            | 9.2070.37  | 92         | 5.95  |
|                | 25            | 28.3570.36 | 113        | 3.35  |

**Paper-Based Analytical Devices for Detection of Water Contamination:** The growing demand for food and water supplies is placing increasing pressure on the quality and quantity of ground and surface water. One environmental concern that has grown in importance in both industrialised and developing countries is the contamination of surface and ground water by nitrate and nitrite. Groundwater is the main source of drinking water for many people worldwide, especially in rural areas. It could become contaminated by human activity or by nature. While nitrate is generally considered safe for human consumption, it can be poisonous and cause various illnesses, such as cancer and blue baby syndrome, when it is transformed into nitrite by denitrifying bacteria in the upper gastrointestinal tract (Mikuška, et al. [24]). The analysis of nitrite and nitrate ions in spiked tap water was performed using the manufactured  $\mu$ PADs and compared with a UV-Visible spectrophotometer. Table 1 shows that, when using  $\mu$ PADs and UV-visible spectrophotometry, respectively, the percentage recovery for a nitrite is 95-99% and 98-100%. Similarly, a nitrate percentage recovery in the range of 96-99% and 96-99 has been observed using  $\mu$ PADs and UV-Visible spectrophotometry, respectively, as shown in (Table 3).

**Table 3:** Nitrite and nitrate analysis in spiked tap water samples using  $\mu$ PADs and UV-Vis spectrometry method.

| Nitrite analysis in Tap water |                                               |                                           | Nitrate analysis in Tap water |                                               |                                           |
|-------------------------------|-----------------------------------------------|-------------------------------------------|-------------------------------|-----------------------------------------------|-------------------------------------------|
| Amount spiked(ppm)            | Percentage Recovery Using $\mu$ PADs analysis | Percentage Recovery using UV-Vis analysis | Amount spiked (ppm)           | Percentage Recovery using $\mu$ PADs analysis | Percentage Recovery using UV-Vis analysis |
| 0                             | -                                             | -                                         | 0                             | -                                             | -                                         |
| 0.5                           | 97.38                                         | 100                                       | 4                             | 96.19                                         | 96.2                                      |
| 0.6                           | 95.39                                         | 98                                        | 6                             | 97.54                                         | 98.27                                     |
| 1                             | 98.74                                         | 99.01                                     | 8                             | 98.14                                         | 98.7                                      |
| 1.2                           | 98.81                                         | 100                                       | 10                            | 99.03                                         | 99.67                                     |

This demonstrates the very good agreement between the  $\mu$ PADs approach and UV-visible spectrophotometry, suggesting that it could be used to analyse nitrite and nitrate without the need for an expensive benchtop analytical device in resource-constrained areas (Tilaye T, et al. [25]). (Tilaye T, et al. [25]) claims that they at last suggest a Nitrite and nitrate contamination in water samples was measured using the colorimetric  $\mu$ -PAD made by screen printing method; the results were compared and confirmed using UV-Vis spectrophotometric analysis. The  $\mu$ -PAD and UV-Vis spectrophotometry results showed excellent agreement in the nitrite and nitrate analysis of spiked tap-water and ground water.

For Determination of Orthophosphate in Tap Water: An inorganic chemical called phosphate is widely used in the manufacturing of paints and coatings, fertilisers, dispersants, flame-retardants for paper, textiles, plastics, coatings, and other materials, as well as in the process of preparing potable (drinking) water. Phosphorus is the limiting nutrient in the majority of freshwater systems, and an excess of it can accelerate eutrophication. The consequences of eutrophication include algal blooms, aquatic plant growth, problems with taste and odour, and oxygen depletion in the water column (Kao, et al. 2022). Because phosphate has a negative impact on the environment, the WHO set a standard allowable limit of 0.1 mg L<sup>-1</sup> for phosphate in drinking water (Herschy [26]). Phosphorus is the limiting nutrient in the majority of freshwater systems, and an excess of it can accelerate eutrophication. The consequences of eutrophication include reduced oxygen levels in the water column, algal blooms, aquatic plant growth, and problems with taste and odour. Most detection techniques are expensive, labour-intensive, and dependent on large quantities of chemicals and samples (Esuneh [27]).

According to reports (Esuneh [27]), the amount of reactive phosphate in water samples could be determined quickly, easily, and affordably by creating microfluidic paper-based analytical devices ( $\mu$ PADs) and employing the wax screen-printing technique. Ascorbic acid and the molybdate/antimony reagent are used in the molybdenum blue method to determine phosphate. The molybdenum blue method of measuring phosphate involves the use of ascorbic acid and the molybdate/antimony reagent. Phosphorus molybdenum blue complex was produced by adding molybdate/antimony reagent to

the paper's hydrophilic circle zone prior to spotting the sample and reducing agent. The complex of colours that resulted was measured with ImageJ software. Numerous parameters influencing the phosphate determination were optimised with RSM's Minitab 19.1.2 program. The UV-Visible spectrophotometry method and the  $\mu$ PAD method demonstrated excellent agreement as shown in a Table 4.

**Table 4:** Reactive phosphate analysis in spiked tap water samples using  $\mu$ -PADs and UV-Visible spectrophotometry method.

| Concentration in Spiked solution (mg/L) | Orthophosphate analysis using UV-Visible Found Concentration |                        |
|-----------------------------------------|--------------------------------------------------------------|------------------------|
|                                         | UV Spectrometer method                                       | $\mu$ PAD method (ppm) |
| 10                                      | 10.04                                                        | 9.85                   |
| 12.5                                    | 12.7                                                         | 12.1                   |
| 15                                      | 15.06                                                        | 15.07                  |

For Determination of Iron in Water Samples: A paper-based microfluidic analytical tool for iron assay that uses photolithography and a photomask made with a 3D printer to print hydrophilic and hydrophobic zones on the paper. For patterning paper-based microfluidic analytical devices, a 3D printer can produce a wide range of customised photomasks fast, easily, and reasonably (Asano, et al. [28]). Finally, a colorimetric method for image processing and quantification based on an iron phenanthroline test that exhibits a colourful reaction with increasing iron concentration was used in Asano, et al.'s investigation of iron in water samples (Table 5). Copper (Cu) is an essential trace element for humans that is involved in numerous biological processes. AgNP, or silver nanoparticles, self-assembles with aminothiols compounds on  $\mu$ PADs to deliver Cu. On the other hand, excessive absorption of Cu would lead to several neurodegenerative diseases, such as Alzheimer's, Parkinson's, and Wilson's. The Chinese Standards for Drinking Water Quality and the World Health Organisation (WHO) set limits of 1 mg/L (15 M) and 1.3 mg/L (20 M) for the amount of copper ion (Cu<sup>2+</sup>) in drinking water, respectively. Consequently, developing effective methods for monitoring the concentration of Cu<sup>2+</sup> in drinking water is crucial. Numerous analytical methods, including atomic absorption spectrometry, electrochemistry, fluorescence, and others, have been developed for the sensitive detection of

Cu<sup>2+</sup>. However, the extent to which these procedures can be performed is limited by the cost of the sophisticated, high-tech equipment and the lengthy treatments involved. Thus, the development of a novel, simple, and useful method for measuring Cu<sup>2+</sup> is essential. Colorimetric verification was performed on the “Copper Detection” application of this sensor, which was utilised to measure Cu<sup>2+</sup> in drinking water through a traditional addition method (Cao, et al. 2019).

**Table 5:** Recovery studies of iron added water samples.

| Water samples | Concentration of Fe/mM |                      |           |
|---------------|------------------------|----------------------|-----------|
|               | Added                  | Present method Found | AAS Found |
| River water   | 0                      | 14.23                | 13.9      |
|               | 9                      | 24.1                 | 23.8      |
|               | 18                     | 33.2                 | 31.7      |
| Tap water     | 0                      | 5.51                 | 5.46      |
|               | 9                      | 14.4                 | 14.3      |
|               | 18                     | 23.5                 | 23.3      |

For Monitoring Organic Molecules in Waste Water Samples: Water pollution is a serious environmental problem that affects millions of people and necessitates routine water quality monitoring. Finding analytical platforms that combine outstanding sensitivity, selectivity, and accuracy with portability, affordability, and user-friendliness is still a challenge. Microfluidic paper-based analytical devices (μPADs) are recognised as a powerful analytical platform capable of fulfilling these requirements. According to (Almeida, et al. [8]), organic chemicals are being used excessively in daily activities (such as household and cosmetic items, agricultural) and have become a significant environmental hazard because they persist in the aquatic environment and have negative long-term impacts on aquatic biota. Pesticides and polycyclic aromatic hydrocarbons (PAHs) are organic pollutants that can have an adverse effect on aquatic ecosystem health. PAHs are present in home and industrial wastewater, agricultural waste, and urban runoff. While chromatographic methods (GC-MS and LC-MS) are widely used to monitor a range of organic contaminants, there is an increasing need for portable and user-friendly sensors. In this regard, Sun, et al. (2014) developed paper-based devices for pentachlorophenol monitoring for water matrices. By evaluating PCP in samples that were tampered with, or made with pure drinking water and river water, researchers were able to evaluate the PEC immunoassay’s analytical validity as well as its practical applicability. Table illustrates how well the results obtained with the μPADs approach agreed with the results obtained with GC-MS. The recoveries of 0.1, 0.5, 1.0, 10.0, and 50.0 ng mL<sup>-1</sup> of PCP were computed using traditional addition techniques. Additional PCP recoveries can be measured, and t-tests showed that the efficiency of the recoveries, which was 100% at a 95% confidence level, did not differ significantly. PCP was tested in spiked samples with various pollutants to assess the analytical reliability and applicability of the PEC immunoassay.

**Detection of Environmental Contaminant & Air Samples**

At the point-of-care, microfluidic devices built on Low Temperature Co-fired Ceramic (LTCC) are utilised as protein biosensors, whole cell-based biosensors, and micro reactors to identify toxins and environmental contaminants. Sensing the environment is essential to personalised health. Numerous microorganisms present in air samples can be identified by resilient and timely disease prevention and control systems. This apparatus works on the Dielectrophoresis (DEP) principle, which involves using unique curved electrodes that attract microorganisms while repelling dust particles to separate an air sample containing pathogenic microorganisms before detection. According to Moon, et al. [29], the fundamental mechanism involves charge-neutral matter travelling at low voltage in an uneven electric field. By measuring colorimetric changes in dosage-dependent fish living cells, a sensitive cell biosensor can identify toxins from *Salmonella enteritis*, *Vibrio parahaemolyticus*, and *Bacillus cereus* as well as other unknown pathogens in water. LEDs are illuminated by chromophores in response to toxins or pathogens, resulting in a change in colorimetric response (Plant, et al. 2004). They can be employed in genetically modified forms or as naturally occurring bioluminescent bacteria (Girotti, et al. [30]). For microbial detection and other bio-analysis, microelectromechanical systems technology in microfluidics is employed; however, the most successful method has been found using a polymerase chain reaction (PCR) microchip or microdevice with thermocycling detection. There are also devices that use DNA microarray hybridisation and capillary electrophoresis (CE) (Zhang, et al. 2006). Prior to now, it was impossible to identify bacteria that were aerosolised and far away. On the other hand, a fibre optic biosensor for environmental analysis can function as a remotely controlled system and run immunoassays in tandem with an automated fluidics unit (Saxenaa, 2014).

**Measurement of Different Gases:** In order to measure gaseous species for environmental analysis, new microsystems and microdevices could be used to monitor various gases (Ohira and Toda, 2008). Fluorescent cellulosic materials and in situ fluorescent oxygen sensing techniques are used to measure carbon cycling involving cellulytic respiring microorganisms. These systems will be able to calculate the atmospheric concentration of CO<sub>2</sub> (Saxenaa, 2014). Moreover, global <sub>2</sub> level detection in the atmosphere is made possible by pore network microfluidic structures that imitate porous media (Grate, et al. [31]).

**For Detection of Particulate Matters:** Hydrogen sulphide is a combustible gas that smells like rotten eggs and is heavier than air. When its concentration in the air surpasses the olfactory perception threshold (300 ppb), it may be harmful to human health and cause symptoms like headaches, nausea, lung irritation, and even death. According to Zhou, et al. [32], hydrogen sulphide is toxic and corrosive, harming electronic components, metallic surfaces, and concrete. According to AS Petrucci, et al. [33], measuring hydrogen sulphide (H<sub>2</sub>S)

in air required the creation of a detection system that comprised mercury acetate (FMA), a 470 nm wavelength spectrometer, a light-emitting diode (LED), and a paper substrate infused with fluorescein. With a LOD of roughly 3 ppb, the apparatus’s reaction time was demonstrated to be less than 60 s.

Measurement of Polycyclic Aromatic Hydrocarbons (PAHs)

For the purpose of analysing organic compounds like polycyclic aromatic hydrocarbons (PAHs), another microfluidic device has been developed. This is a four-layered microchip that offers sensitive and independent analysis when paired with a microfluidic analyser. The capillary electrophoresis (CE) phenomenon serves as the foundation for the Multichannel Mass Organic Analyser (McMOA). This apparatus detects benzo[a]pyrene and perylene in samples using a fluorescence-based assay. According to Benhabib, et al. [34], it might also be applied to the analysis of organic compounds for space exploration and research.

Heavy Metals

A solid-phase bioactive lab-on-paper sensor is a microfluidic device based on paper that employs the sol-gel method to entrap reagents using inkjet printers. In environmental samples like tap water or lake water, they offer a colorimetric enzymatic assay for -galactosidase (B-GAL) that allows for the simultaneous detection of multiple heavy metals. Nonetheless, the methodology remains unaffected by the existence of potassium or sodium ions in water samples (Hossain, et al. [35]). Mentele, et al. (2012) describe the use of microlitres of sample for colorimetric detection of Fe, Cu, and Ni in a microfluidic paper-based device for occupational exposure to metal-containing aerosols. The multilamination technique was used to create another microfluidic device. Lead concentrations in environmental samples can be measured with this instrument (Punjiya, et al. [36]) (Tables 6 & 7).

Table 6: Determination of total in spiked soil samples with PADs and UV-Viibile spectrometry.

| Method                   | Amount spiked/<br>µg g <sup>-1</sup> | Amount found         |                                      | Amount determined before addition |                                      | Recovery<br>(µg g <sup>-1</sup> ) | Recovery (%) |
|--------------------------|--------------------------------------|----------------------|--------------------------------------|-----------------------------------|--------------------------------------|-----------------------------------|--------------|
|                          |                                      | Mean image intensity | Concentration/<br>µg g <sup>-1</sup> | Mean image intensity              | Concentration/<br>µg g <sup>-1</sup> |                                   |              |
| µ-PADs                   | 360                                  | 132.0 ± 1.3          | 1208 ± 57                            | 84.4 ±                            | 810 ± 126                            | 397                               | 110          |
| UV-Vis Spectrophotometry | 360                                  |                      | 1055                                 |                                   | 735 ± 53                             | 320                               | 89           |

Table 7: Results of the standard addition of Cu<sup>2+</sup> in drinking water.

| Spiked (µM) | Found (µM) | Recovery (%) | Relative standard deviation (%) |
|-------------|------------|--------------|---------------------------------|
| 4           | 4.38       | 109.5        | 8.3                             |
| 10          | 10.32      | 103.2        | 3.9                             |
| 15          | 15.9       | 106          | 2.9                             |
| 20          | 20.04      | 100.2        | 2.1                             |

**For Determination of Total Chromium in Soil Samples:** Despite their persistence and lack of biodegradability, heavy metals are a major global health and environmental threat (Arora, et al. 2008). Human health may be at risk from excessive exposure to trace elements through the food chain, skin contact, or ingestion of soil-borne trace elements (Hooda [37]). For the first time, colorimetric-based µPADs developed by (Muhammed, et al. [38]) in Ethiopia were used to determine the total Cr in soil collected from an industrial region in Kombolcha town. They concluded that the total Cr values in all of the soil samples were higher than permitted. Furthermore, the soils were

found to be moderately to substantially contaminated with Cr when the geo-accumulation index was used to determine the level of Cr contamination. Table 8 reports the percentage recoveries from the UV-Vis and µPAD spectrophotometry measurements, which were 89% and 110%, respectively. The two recoveries fall inside the allowed ranges. The technique based on µPAD was verified through the use of ultraviolet-visible (UV-Vis) spectrophotometry. The results of the study have enormous potential for putting the WHO’s ASSURED policy into practice, particularly in resource-poor nations like Ethiopia.

**Table 8:** Paper based sensors for H2S determination.

| Detection Method | Response time | LOD    | Sensor                     |
|------------------|---------------|--------|----------------------------|
| Electrochemical  | 20 min        | 15 ppm | Polyaniline                |
| Electrochemical  | 20 min        | 10 ppm | Copper acetate             |
| Optical          | 15 min        | 2 ppb  | Palladium-based            |
| Visual           | 30 min        | 30 ppb | Bismuth-based              |
| Optical          | 10 s          | 50 ppb | Lead acetate               |
| Optical          | 2.5 min       | -      | Methyl green               |
| Optical          | 60 s          | 3 ppb  | Paper-based sensors (μPAD) |

**Current μPADs System for Environmental Applications**

Even with their low cost, small sample and reagent volumes, portability, and quick response times, μPADs still have a few obstacles to overcome before they can be widely used in the field. There have been few large-scale field demonstrations of μPAD capabilities; one example that comes to mind is a biomedical test for transaminase detection as a marker of drug-induced liver injury. While some research studies utilising environmental PADIs have documented the examination of real-world samples returned to the laboratory, these were primarily small-scale investigations, and the devices are still not as field-ready as their biomedical equivalents. Sicard, et al.'s recent work is one noteworthy exception. In their initial trials, they combined smartphone analysis with paper sensor detection of organophosphate pesticides. Using the GPS on the smartphone, the outcome, time, and location of each analysis were uploaded to a central web server. The benefits that this collaborative mapping technique offers can be used for early detection or for large-scale, long-term environmental monitoring of hotspots for contamination.

Widespread implementation of a rapid response test requires on-site analysis. Colorimetric detection has proven to be one of the easiest (and least expensive) techniques for determining the target. Differentiating colour intensity visually (i.e., without the use of optical instruments) is semi-quantitative and has been demonstrated to differ between individuals. While colorimetric detection with the aid of a scanner or camera for image acquisition can increase method accuracy, it can also limit field use and increase analysis costs. Some have recently reported semi-quantitative alternatives to intensity-based colorimetry that do not require imaging, like count-, distance-, and

time-based μPADs. In count-based detection, the number of bars, tabs, or spots that turn colour is counted to determine the concentration. Using an on- or off-device ruler, one can measure the distance of continuous colour development along a channel to accomplish distance-based quantification. By using a time-based quantification method, the concentration of a test zone and a control zone is correlated with the time difference for colour development.

Since smartphones and camera phones are now widely available, the cost of developing new sensors has dramatically dropped because the phone serves as both a data transmission source and a detector. For instance, new software has been created to use a smartphone to perform intensity-based colorimetric measurements in the field. A colorimetric μPAD for assessing water's pH and nitrite content simultaneously was recently described by Lopez-Ruiz et al. (Figures 4 & 5). The μPAD was photographed using a specialised smartphone application, and the hue-saturation-brightness indices were correlated with the pH and nitrite concentration of the solution using a software algorithm. By creating an application to show the ideal angle and distance between the user and the finished device, Park et al. extended this technique. Electrochemical measurements on μPADs have also been conducted using smartphone analysis protocols. For instance, Delaney et al. recently described a method in which they adjusted the audio output's waveform and amplitude using a smartphone as a potentiostat. Furthermore, some devices have implemented quick response (QR) codes, which may be used in the future to communicate essential diagnostic or identifying information about the sample without requiring user input. The identification of samples would facilitate automated and enhanced collection of field data. Subsequent instances employing smartphone technology will persist in transforming PAD application, permitting additional field implementation.

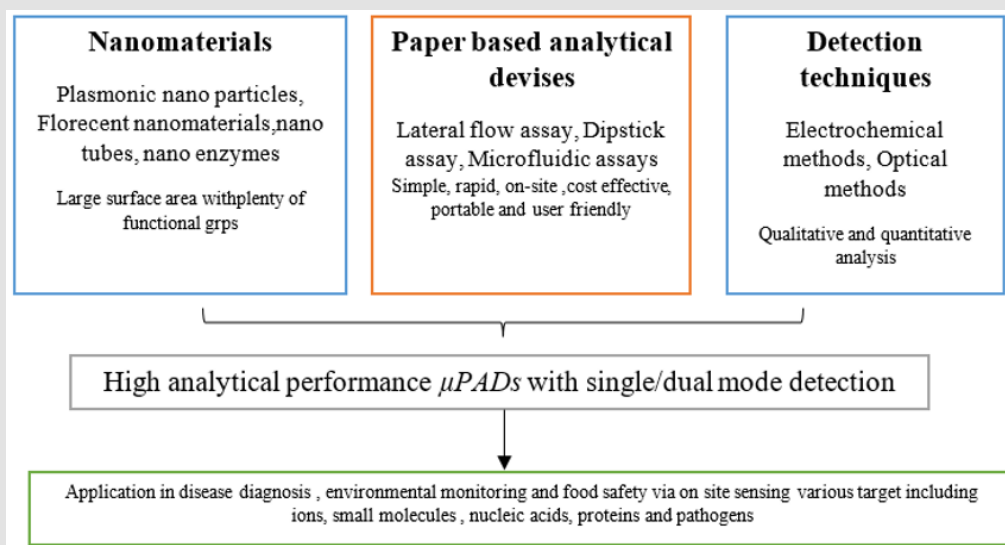


Figure 4: Outline of nanomaterial-based paper based analytical devises.

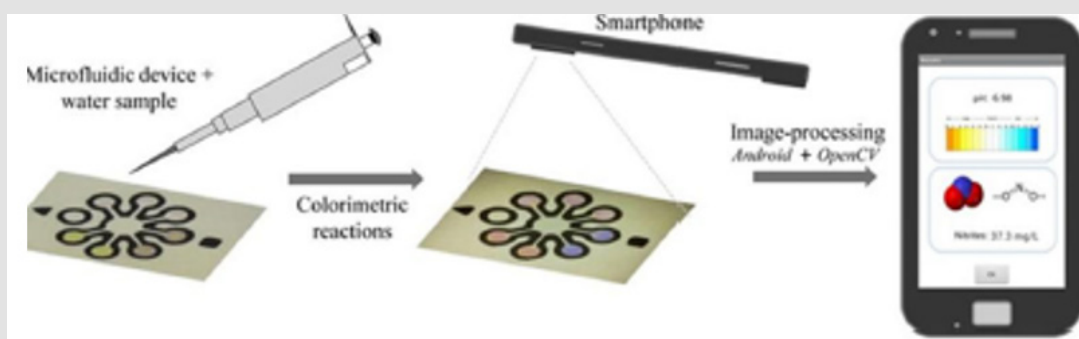


Figure 5: Use of a smartphone to conduct intensity-based measurements.

In bench research, the nanomaterial-based PADs have achieved remarkable success in sensing a wide range of targets, including ions, small molecules, nucleic acids, proteins, and pathogens. Nevertheless, only a small number of proof-of-principle analytical devices have been turned into commercial goods (Pang, et al. 2022).

In order to improve the longevity, robustness, and reliability of real-time monitoring, more efforts should be made to develop novel strategies. These strategies primarily depend on the synthesis of ad-

vanced nanomaterials, the introduction of multiple detection modes and a new sensing mechanism, the development of a trustworthy microfabricating methodology/standard, and the simplification of detection procedures. The next generation of PADs will be multiplexed, easy to use, and affordable. They will be capable of on-site qualitative and quantitative analysis using portable devices like wearable electronics and smartphones, as well as by using the naked eye (Table 9) [39-80].

**Table 9:** Determination of total Cr in spiked soil samples with  $\mu$ PADs and UV-Vis spectrometry.

| Method                   | Amount spiked<br>$\mu\text{g g}^{-1}$ | Amount found         |                                       | Amount determined before addition |                                       | Recovery<br>$\mu\text{g g}^{-1}$ | Recovery% |
|--------------------------|---------------------------------------|----------------------|---------------------------------------|-----------------------------------|---------------------------------------|----------------------------------|-----------|
|                          |                                       | Mean image intensity | Concentration<br>$\mu\text{g g}^{-1}$ | Mean image intensity              | Concentration<br>$\mu\text{g g}^{-1}$ |                                  |           |
| $\mu$ -PADs              | 360                                   | 132.0 $\pm$ 1.3      | 1208 $\pm$ 57                         | 84.4                              | 810 $\pm$ 126                         | 397                              | 110       |
| UV-Vis Spectrophotometry | 360                                   | -                    | 1055                                  | -                                 | 735 $\pm$ 53                          | 320                              | 89        |

Conclusion and Future Perspectives

Paper-based assays have been widely used in chemical research since their first applications, beginning with litmus filter substrate. Developing analytical devices using filter paper as a resource for investigation was initially slow. Since 2007, this field of study has exploded. The newest generation of lab-on-a-chip technologies, microfluidic paper-based analytical devices ( $\mu$ PADs), have achieved considerable advancements in both our comprehension of fundamental behavior and performance characteristics and the development of their applications. Microfluidic paper-based instruments for detecting various antioxidants, heavy metals, food additives, contaminants in the air, soil, and water, explosives, quality-control problems, diseases, analyses, pesticides, and insecticides that have been documented to date in light of the a for ementioned issues and analysis,  $\mu$ PADs are a developing technology that, especially in situations with limited resources, offers quick, affordable, and simple-to-use advantages. Although the area of microfluidic paper-based sensors has grown quickly, there are still many problems to be solved  $\mu$ PADs’ analytical performance, including sensitivity, selectivity, repeatability, stability, and multiplexed analysis, can be enhanced by using nanomaterials and nanotechnology.

Microfluidic devices have the advantages of being simple to use, inexpensive to produce, and simple to dispose of after use. Traditional instruments such as atomic absorption spectroscopy (AAS), atomic emission spectroscopy (AES), and inductively coupled plasma spectroscopy (ICP-MS) are overcome by this technology. Because these instruments are costly and difficult to obtain, the advancement of microfluidics will soon overcome all disadvantages. The disadvantage of microscale detection is that microfluidic channels can become clogged by fine particulate matter or bubble formation; however, using fine filters at the sampling point can reduce clogging but is an expensive approach. The molecular mechanism of the microfluidic electrolytic cell (MEC) is unknown. Because on-line sample preparation on the PCR microfluidics takes longer, several improvements for automated rapid detection are still required. The demand for more efficient technologies to restore ecosystems appears to have increased interest in the research and development of microfluidic technologies for environmental applications.

While traditional applications of microfluidics have focused on detection and analysis, droplet-based microfluidics has recently fo-

cused on the development of functional microparticles for environmental remediation. However, the greatest challenge for the use of microfluidic systems in the effective treatment of water and air pollutants remains the technical and economic barriers to industrializing microsystems or micro technologies so that they can be employed or retrofitted into currently available industrial technologies. The majority of microsystems today are generally limited to a “one-design-one-application” basis, which means that more customization work is required to expand the functionality for other applications due to highly functionalized design for each system. Without a doubt, microfluidic technology is still in its infancy and is an emerging area of technological development with enormous potential, particularly in the field of environmental care. Microfluidics academic research is required for the development of new nanomaterials, processes, and functionalities. Standardization, automation, and high throughput should be the focus of the research.

Declaration

Ethics Approval and Consent to Participate

“Not Applicable (NA)”.

Consent for Publication

“Not Applicable (NA)”.

Availability of Data and Materials

Not Available.

Competing Interests

The authors declare that there is no competing interest.

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The author compiled the manuscript and edited the manuscript. All authors read and approved the final manuscript.

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## Authors' Contributions

Tewodros and Dessie contributed to the conception of the study. Tewodros organized conducted the literature search, interpreted the data and prepared the manuscript. Dessie and Yezbie, the supervisors of the review paper took part in interpreting the data, Dessie, Agmas, Marye and Zerubabel provided guidance on the review of the literature and the direction of the work, and made critical revisions that substantially improved the manuscript. The author(s) read and approved the final manuscript.

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