



Miniaturized And Portable Analytical Devices For On-Site Chemical Analysis

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ABSTRACT:

Modern technological advancements have accelerated the development of miniaturized and portable analytical devices, enabling on-site, real-time, and decentralized chemical analysis. Traditional laboratory instruments, although highly accurate and sensitive, are often bulky, expensive, and require skilled personnel. Portable analytical devices overcome these limitations through miniaturization of components, integration of microfluidics, smartphone-assisted detection, point-of-care diagnostics, and the use of nanomaterials.

These devices allow rapid screening of chemicals in environmental monitoring, food safety, forensic investigations, pharmaceuticals, toxicology, and biomedical diagnostics. The increasing demand for low-cost, fast, and user-friendly analytical solutions has driven innovations in lab-on-a-chip (LOC), paper-based microfluidics, portable spectrometers, electrochemical sensors, and handheld chromatographic systems.

This review provides an extensive overview of the types, working principles, fabrication methods, influencing factors, advantages, limitations, and future prospects of miniaturized analytical systems.

Keywords: Portable sensors, lab-on-a-chip, on-site analysis, microfluidics, handheld spectrometers.

INTRODUCTION:

Analytical chemistry has traditionally depended on large, sophisticated, and laboratory-based instruments for the qualitative and quantitative analysis of chemical substances. While such instruments provide high precision, accuracy, and sensitivity, their size, cost, operational complexity, and requirement for controlled laboratory environments limit their use for real-time or field-based applications. In many situations—such as environmental monitoring, food adulteration testing, forensic investigations, and emergency toxicology—chemical analysis is needed immediately at the sampling

site, where conventional instruments cannot be transported.

To overcome these limitations, modern research has focused on developing miniaturized and portable analytical devices capable of performing rapid, on-site chemical analysis. These devices combine advanced technologies such as microfluidics, nanotechnology, electrochemical sensing, optical detection systems, smartphone integration, and Lab-on-a-Chip (LOC) platforms, allowing laboratory-level analytical performance in compact, user-friendly formats.

Miniaturized analytical systems significantly reduce sample volume, reagent usage, analysis time, and eliminate delays caused by sample transportation. Their ability to generate real-time results with minimal expertise makes them extremely valuable in remote, resource-limited, or time-critical scenarios. Devices such as handheld spectrometers, portable Raman analyzers, paper-based microfluidic devices (μ PADs), and smartphone-assisted detection systems are increasingly used for environmental pollutant analysis, biomedical diagnostics, pharmaceutical quality testing, and industrial safety monitoring.

The evolution of these technologies supports the global transition toward decentralized analytical testing, where accurate chemical analysis can be performed outside the laboratory by using portable, efficient, and cost-effective devices. The present review focuses on the development, classification, advantages, limitations, fabrication strategies, and future prospects of miniaturized and portable analytical devices designed for on-site chemical analysis.^[2]

TECHNOLOGICAL EVOLUTION OF PORTABLE ANALYTICAL DEVICES:

The development of portable analytical devices has undergone a remarkable transformation over the last few decades. This evolution reflects continuous advancements in **microengineering, material science, sensor technology, electronics, and computational algorithms**, which together have enabled complex analytical procedures to be conducted outside conventional laboratory environments.

Initially, analytical instruments were extremely large, heavy, and power-dependent, restricting their use to controlled laboratory settings. However, the need for **rapid, on-site chemical detection** in fields such as environmental monitoring, defense, biomedical diagnostics, and forensic analysis prompted innovations that gradually led to their miniaturization. The evolution can be divided into four major technological phases:

1. First Phase – Conventional Portable Tools (Pre-1980s):

This early phase included **rudimentary handheld tools** used for basic analytical tasks such as:

- Portable **pH meters**
- Handheld **turbidity meters**
- Pocket-sized **refractometers**
- Simple **color comparison kits**

These instruments allowed some level of field-based chemical measurement but suffered from:

- Poor sensitivity
- Limited accuracy
- Manual sample manipulation
- Narrow analytical capability

They primarily served as screening tools, requiring confirmation using laboratory instruments.^[3]

2. Second Phase – Sensor-Based Miniaturization (1980s–2000):

With the invention and commercialization of **electrochemical sensors**, the analytical field experienced major improvements. Innovations included:

- **Ion-selective electrodes (ISEs)**
- **Portable electrochemical analyzers**
- **Optical sensors** (LED-based detection)
- **Gas sensors** for toxic gas monitoring

These instruments provided higher sensitivity, portability, and faster response times. Key technological improvements included:

- Microelectronic circuits for signal amplification
- Development of **disposable sensor strips**
- Polymer membranes for selective analyte detection

This phase saw the first medical portable analyzer: the **glucose meter**, revolutionizing point-of-care diagnostics.

2. Third Phase – Lab-on-a-Chip & Microfluidics Era (2000–2015):

This phase marked a dramatic leap forward. With the emergence of **microfluidics**, complex laboratory operations were miniaturized into small, portable formats.

Breakthrough technologies included:

- **Lab-on-a-Chip (LOC)** devices
- **Micro Total Analysis Systems (μTAS)**
- **Paper-based microfluidics (μPADs)**
- Integrated **microreactors** and **micropumps**

These devices incorporated:

- Sample preparation
- Chemical reaction
- Mixing and separation
- Detection

onto a single micro-scale platform. Advantages brought by this era:

- Extremely low sample and reagent consumption
- Faster analysis
- Low-cost mass manufacturing using PDMS, glass, or plastics
- Suitability for point-of-care testing in remote settings

3. Fourth Phase – Digital, AI-Integrated, & Smartphone-Assisted Devices (2015– Present):

Modern portable analytical devices merge **smart sensors, nanotechnology, wireless connectivity, and artificial intelligence.**

Current innovations include:

- Smartphone-based colorimetric and fluorometric analyzers
- Bluetooth-enabled electrochemical sensors
- Nanomaterial-enhanced biosensors (graphene, gold nanoparticles, CNTs)
- Handheld **Raman, FTIR, and NIR spectrometers**
- Mini-GC and mini-MS systems
- Cloud-connected diagnostic devices

Advantages of the latest generation include:

- Automated data interpretation
- Real-time mapping and remote monitoring
- Enhanced sensitivity using plasmonic nanomaterials
- Machine learning for pattern recognition

This era has established portable devices as **critical tools** in healthcare, environmental protection, food safety, and emergency response^[3]

ADVANTAGES:

Portable analytical devices offer multiple benefits that support their growing use in chemical, biomedical, environmental, and industrial applications. These advantages arise from miniaturization, low power consumption, and integration of modern detection technologies.

1. Real-Time and On-Site Detection

These devices eliminate delays caused by transporting samples to laboratories, enabling immediate decision-making in critical situations such as contamination, poisoning, or industrial hazards.

2. Reduced Sample and Reagent Consumption

Microfluidic and miniaturized devices require only microliters of sample, making them cost-effective and environmentally friendly.

3. Improved Portability

Lightweight and compact designs allow testing in remote and resource-limited environments.

4. Faster Analytical Response

Minimal sample preparation leads to rapid results, which is essential for emergency diagnosis, field inspections, and routine monitoring.

5. Enhanced Safety

Testing hazardous materials at the sample site reduces risks associated with sample handling, transport, or exposure.

6. User-Friendly Operation

Most portable sensors are designed for non-specialists, featuring simple interfaces, automated functions, and quick interpretation.

7. Cost-Effective Analysis

Lower infrastructure requirements, reduced reagent usage, and simplified workflows significantly lower overall testing costs^[4]

DISADVANTAGES:

1. Lower Sensitivity Compared to Laboratory Instruments

The miniaturization of optical paths and electrodes may reduce analytical sensitivity and detection capabilities.

2. Limited Dynamic Range

Portable sensors sometimes struggle to measure extremely high or extremely low analyte concentrations.

3. Environmental Interference

Temperature, humidity, dust, and light exposure can affect sensor stability and accuracy during field use.

4. Need for Frequent Calibration

Portable devices may require repeated calibration due to environmental variations, aging components, or drift in sensor response.

5. Limited Lifespan of Disposable Components

Paper-based devices, microfluidic chips, and electrodes may degrade over time, reducing long-term reliability.

6. Battery Dependency

Continuous operation depends on battery life, limiting functionality in remote environments without power access.

7. Restricted Separation Efficiency

Miniaturized chromatographic systems cannot fully match the separation performance of full-scale laboratory instruments.

8. Potential for Signal Noise

Miniaturized electronics may generate background noise, affecting precision and quantitative analysis^[4].

IDEAL CHARACTERISTICS OF PORTABLE ANALYTICAL DEVICES:

An ideal miniaturized or portable analytical device should demonstrate high analytical efficiency while being user-friendly, cost-effective, and capable of functioning in diverse field environments. To address the limitations of traditional laboratory instruments, these devices must exhibit certain essential characteristics that ensure reliable on-site performance.

1. High Sensitivity and Selectivity

The device should accurately detect low concentrations of analytes with minimal interference from surrounding chemicals or matrix components. Sensors must distinguish between closely related chemical species, especially in complex samples such as blood, soil, or wastewater.

2. Minimal Sample and Reagent Requirements

The use of microfluidic systems allows processing of samples in microliter quantities. This reduces operational cost, lowers waste generation, and enables analysis where sample volume is limited.

3. Rapid Response Time

The device should provide results within seconds to minutes to support critical decision-making in healthcare, environmental monitoring, and emergency response situations.

4. Portability and Compact Design

A lightweight design enables convenient field usage. Devices must be small enough to fit in a hand or pocket, and easy to transport across different terrains and conditions.

5. Low Power Consumption

Battery-operated or energy-efficient systems ensure continuous operation even in remote or resource-limited environments. Integration with rechargeable or solar-powered systems adds significant advantage.

6. Robustness and Durability

Field analysis requires the device to withstand harsh environmental conditions such as temperature fluctuations, humidity, dust, and mechanical stress. The device should also maintain calibration stability over extended use.^[5]

7. Ease of Operation

Devices should feature intuitive interfaces, automated detection processes, and simplified calibration procedures. This allows non-specialist users to conduct reliable chemical testing with **minimal training**.

8. Cost-Effectiveness

Affordable device fabrication using materials like polymers, paper substrates, or inexpensive optical and electronic components enhances accessibility.

9. Data Processing and Connectivity

Integration with smartphones, Bluetooth, Wi-Fi, or cloud systems enables:

- Real-time data sharing
- Remote diagnostics
- Automated analysis
- Data storage and mapping

10. Versatile Applicability

The device should support detection of multiple analytes and be adaptable for various domains such as food safety, pharmaceuticals, water quality, industrial inspection, and biomedical diagnostics.

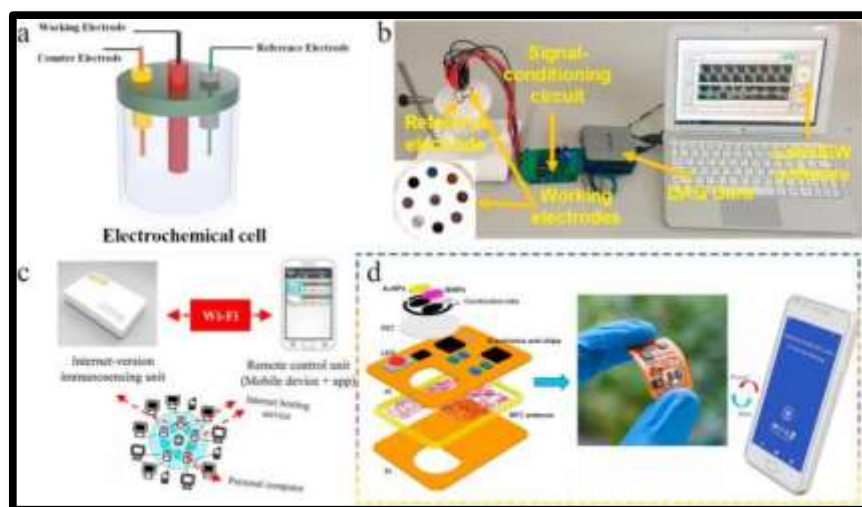


FIGURE 1: Portable Electrochemical Sensor

CLASSIFICATION OF PORTABLE ANALYTICAL DEVICES:

Portable analytical devices can be categorized based on several criteria including detection mechanism, analytical platform, mode of operation, and application domain. Each class offers unique advantages for field-based chemical analysis.

A. Based on Detection Principle

1. Optical Devices

Use light-matter interaction for detection. Examples:

- Portable UV-Visible spectrometers
- Handheld Raman analyzers
- LED-based fluorescence detectors
- Smartphone colorimetric devices

Advantages:

- Non-destructive
- Fast response
- High sensitivity

2. Electrochemical Devices

Operate on electrical signals generated from chemical reactions. Types include:

- Potentiometric sensors
- Amperometric biosensors
- Voltammetric analyzers Widely

used in:

- Glucose monitoring
- Heavy metal detection
- Toxic gas analysis

3. Mass-Based Devices

Use changes in mass or vibration frequency. Examples:

- Quartz Crystal Microbalance (QCM)
- Surface Acoustic Wave (SAW) sensors

Applications:

- VOC detection
- Pathogen sensing

4. Thermal Sensors

Measure changes in heat during chemical reactions. Examples:

- Microcalorimeters
- Thermal conductivity analyzers Useful in:
- Gas detection
- Reaction monitoring

B. Based on Analytical Platform

1. Lab-on-a-Chip (LOC) Systems

LOC devices integrate multiple laboratory processes into a microchip. Characteristics:

- Microliter-level fluid handling
- High accuracy
- Integration of sensors, pumps, valves

Applications:

- Diagnostics
- Environmental analysis

2. Microfluidic Paper-Based Analytical Devices (μ PADs)

Made from patterned paper that controls fluid flow via capillary action. Advantages:

- Low cost
- Disposable
- No external pumps required

Used for:

- Clinical diagnostics
- Food quality analysis

3. Portable Spectroscopic Devices

Handheld instruments used for non-invasive chemical analysis. Popular examples:

- Handheld Raman spectrometers
- NIR analyzers
- FTIR spectrometers

Applications include:

- Pharmaceutical identification
- Hazardous materials detection

4. Portable Chromatographic Systems

Miniaturized versions of gas and liquid chromatography systems. Features:

- Integrated microcolumns
- On-chip detectors
- Rapid separation

5. Smartphone-Based Detection Systems

Utilize the smartphone's camera, flash, and processor. Applications:

- Colorimetric assays
- Fluorescence measurements
- Image-based quantification

C. Based on Application Area

1. Environmental Monitoring Devices

Used for detecting pollutants such as:

- Heavy metals
- Pesticides
- Toxic gases

2. Biomedical Diagnostic Devices

Examples:

- Glucose meters
- Lateral flow immunoassays
- Portable blood analyzers

3. Food Safety Devices

Used for:

- Adulteration detection
- Spoilage monitoring
- Pathogen identification

4. Industrial and Pharmaceutical Devices

Used for:

- Process monitoring
- Raw material verification
- Impurity testing^[5]

FACTORS AFFECTING THE PERFORMANCE OF PORTABLE ANALYTICAL DEVICES:

1. Sample Matrix Interference

The composition of the sample greatly affects device performance, especially when proteins, salts, organic compounds, or suspended particles interact with the sensing surface. These interfering substances can suppress or enhance signal, leading to deviations in accuracy. Field samples without pre-treatment often show stronger matrix effects. Such interference reduces selectivity and may alter sensor response over time.

2. Temperature and Environmental Conditions

Portable devices are highly sensitive to environmental variations such as temperature, humidity, dust, and exposure to sunlight. Temperature fluctuations may change reaction kinetics, electrode conductivity, or optical absorbance, causing signal drift. High humidity can damage paper-based microfluidic devices and distort readings. Outdoor field conditions therefore require robust device housing and compensation mechanisms.

3. Material and Device Design

The performance and stability of portable devices depend greatly on sensor material, electrode surface area, microchannel geometry, and optical path length. Miniaturized sensors often generate lower signal intensities due to reduced detection surface or shorter optical paths. Poor fabrication quality or

inconsistent microchannel design may lead to variations between tests. These factors directly influence sensitivity, reproducibility, and overall device functionality.

4. Calibration and User Handling

Most portable analytical devices require frequent calibration because their signals drift more in field environments than laboratory instruments. Improper user handling—such as incorrect sample volume, uneven application on test strips, or contamination—can introduce significant error. Since many devices are used by non-specialists, variations in technique often affect the reliability of readings. Accurate performance depends on consistent user operation.

5. Battery Power and Signal Processing

Low battery levels can weaken detector output, slow down data processing, or interrupt measurements, especially in electronic and optical devices. Miniaturized sensors often produce weak signals that require strong noise filtering, and poor signal-to-noise ratios can distort final results. The effectiveness of built-in algorithms for baseline correction, filtering, and quantification significantly influences device performance.

6. Signal Stability and Sensor Drift

Over time, portable sensors may experience drift due to continuous exposure to environmental stress, repeated usage, or degradation of sensing materials. Drift causes gradual changes in baseline readings even without analyte presence, reducing long-term reliability. This challenge is more common in electrochemical sensors where electrode fouling or oxidation occurs. Regular recalibration and stable sensor coatings are essential to maintain accuracy.

7. Interference from External Contaminants

Dust particles, moisture droplets, oils from fingers, or residual chemicals on the device surface can interfere with both optical and electrochemical detection. Such contaminants may scatter light, block microchannels, or generate unwanted background signals. Field environments often expose devices to unpredictable contaminants, making protective casings and proper cleaning essential. Even small contaminants can significantly alter low-signal measurements^[6]

METHODS OF MINIATURIZATION:

Miniaturization is the foundation behind the development of portable analytical devices, enabling laboratory processes to be integrated onto compact, lightweight, and low-power platforms. Miniaturization aims to reduce device size, sample volume, reagent consumption, and analysis time while maintaining or improving analytical performance. Several engineering, material science, and

microfabrication techniques contribute to creating efficient handheld analytical tools. The following methods represent the primary approaches used in the development of miniaturized chemical analysis systems.

1. Microfabrication Techniques

Microfabrication involves the creation of micro-scale structures, channels, electrodes, and functional components using processes borrowed from semiconductor manufacturing.

a. Photolithography

- The most widely used technique for patterning microfluidic channels and electrodes.
- Involves transferring a geometric pattern from a photomask onto a light-sensitive material (photoresist).
- Provides high precision and reproducibility.

b. Soft Lithography

- Uses elastomeric molds (commonly PDMS) to replicate microstructures.
- Low-cost, flexible, and suitable for rapid prototyping.

c. Etching (Dry and Wet)

- Removes material from substrates such as silicon or glass to form microchannels.
- Dry etching (plasma etching) offers high resolution.
- Wet etching uses chemical solutions to dissolve material selectively.

d. Laser Micromachining

- Creates precise microchannels, holes, and patterns using high-energy laser beams.
- Suitable for polymer, metal, and glass substrates^[6]

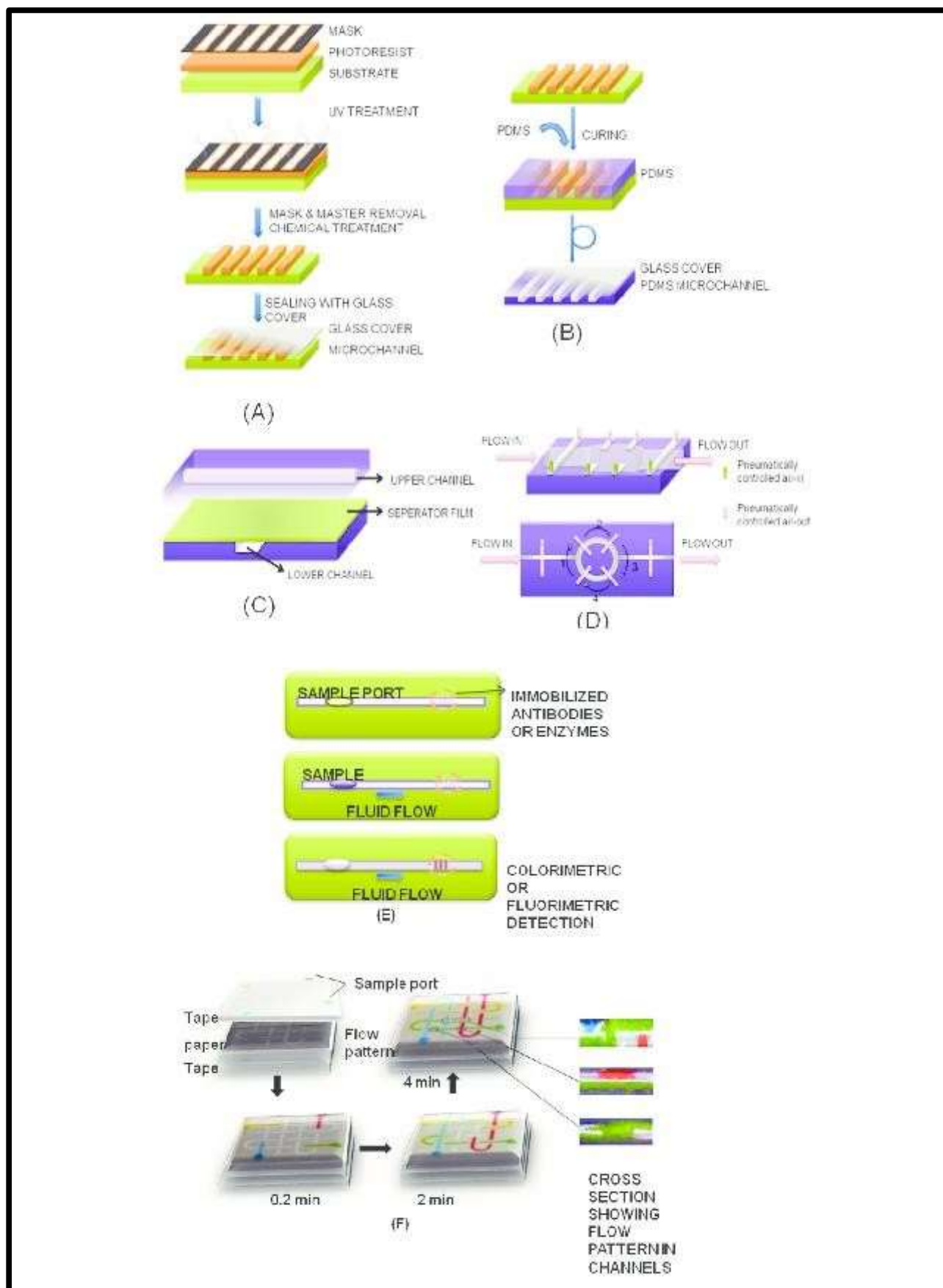


FIGURE 2: Microfabrication Techniques for Miniaturized Devices

2. Microfluidics Integration

Microfluidics is central to miniaturization, allowing complex sample handling operations on a microscale.

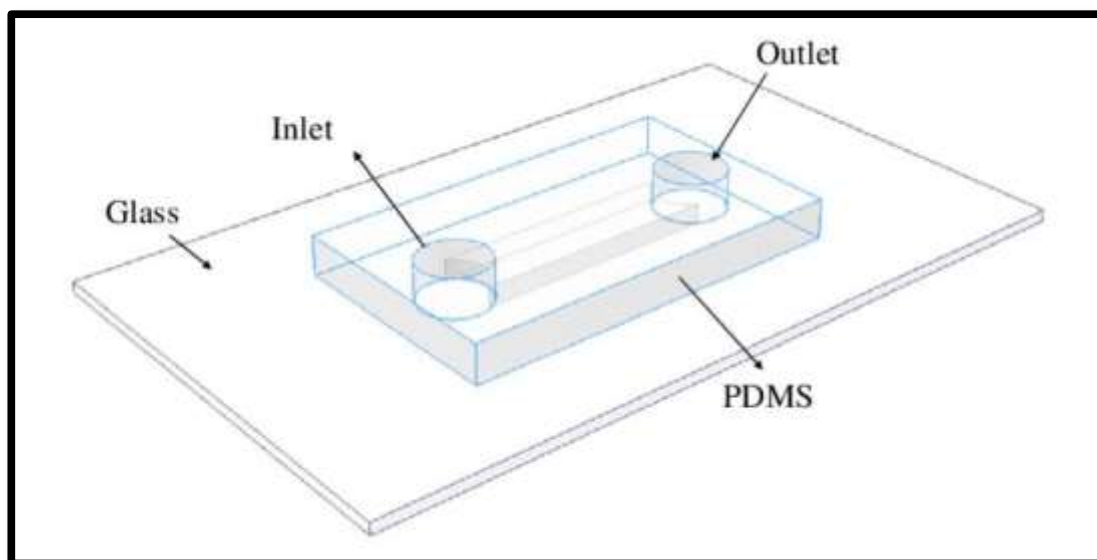


FIGURE 3: Microfluidic Chip Layout

a. Microchannels and Micropumps

Miniaturized channels guide fluids via:

- Capillary action
- Electrokinetic flow
- Pressure-driven flow

Micropumps and microvalves regulate movement and distribution.

b. Sample Mixing and Separation

Microfluidic chips incorporate:

- Micromixers
- Microreactors
- Separation zones

These enable reactions and analytical operations inside small channels.

c. Paper-Based Microfluidics (μ PADs)

Paper is patterned using wax printing or inkjet printing to create fluid pathways. Advantages:

- Extremely low cost
- No pumps required

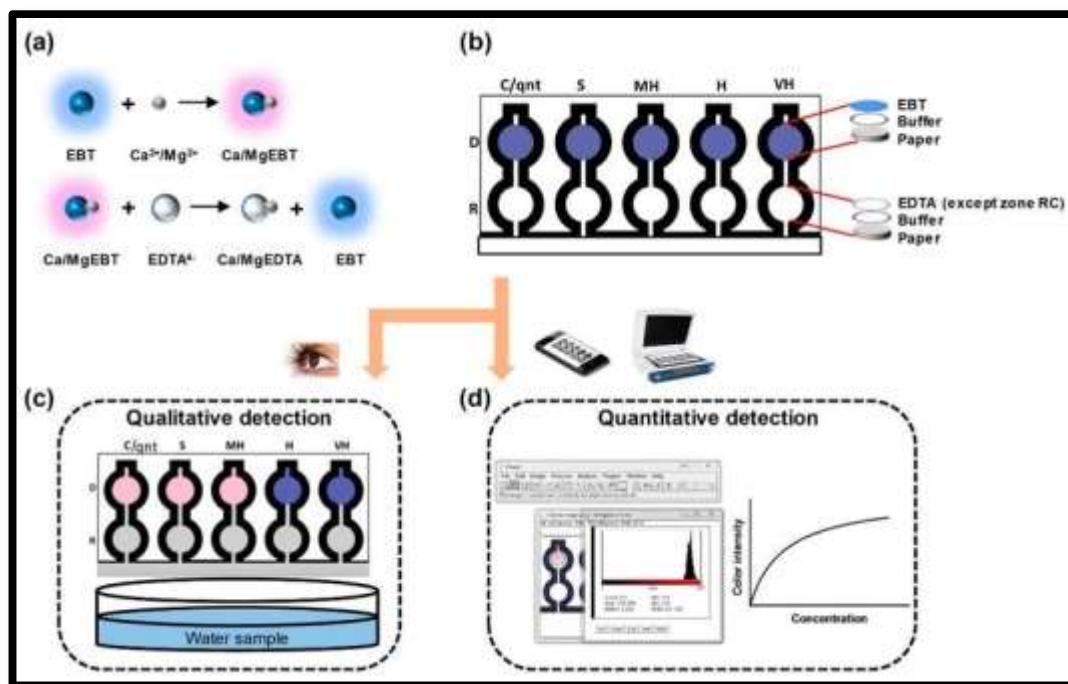


FIGURE 4: Paper-Based Microfluidic Device (μ PAD)

3. Sensor Miniaturization

Reducing the size of sensing components while maintaining sensitivity is key to device portability.

a. Nano-Enabled Sensors

Nanomaterials used include:

- Gold nanoparticles
- Carbon nanotubes (CNTs)
- Graphene
- Quantum dots These

enhance:

- Sensitivity
- Surface area
- Signal amplification

b. Miniaturized Electrodes

Microelectrodes improve:

- Faster electron transfer
- Reduced noise
- Higher current density

Used in portable electrochemical analyzers.

c. **Optoelectronic Miniaturization**

Includes:

- Mini-LEDs
- Micro-photodiodes
- CMOS sensors

Allow compact optical detection systems in portable spectrometers.

4. Integration of Electronics and Embedded Systems

The incorporation of microelectronics enables intelligent, automated, and efficient on-site analysis.

a. **Microcontrollers and Microprocessors**

Provide functions such as:

- Signal processing
- Data acquisition
- Calibration management

b. **Wireless Communication Modules**

Bluetooth, NFC, Wi-Fi allow:

- Wireless data transfer
- Smartphone connectivity
- Cloud-based analysis

c. **Miniaturized Power Systems**

Portable devices use:

- Rechargeable batteries
- Low-power electronics
- Solar-powered modules

5. Lab-on-a-Chip (LOC) and Micro Total Analysis Systems (μ TAS)

LOC systems integrate multiple laboratory processes — including sample preparation, mixing, separation, and detection — onto a single microchip.

Key features:

- Microliter-scale reagent use
- Highly compact
- High analytical precision

μ TAS expands this concept to fully automated systems capable of complete analysis with minimal user input.

6. Additive Manufacturing (3D Printing)

3D printing allows rapid fabrication of customized microfluidic devices, sensor housings, and structural components.

Advantages:

- Rapid prototyping
- Low material waste
- Complex geometries are possible

Materials include:

- Photopolymers
- Resins
- Thermoplastics

This method democratizes device fabrication by reducing manufacturing barriers.

7. Smartphone Integration and Digital Miniaturization

Smartphones serve as powerful analytical platforms due to their:

- High-resolution cameras
- LED flashlights
- Strong processing power
- Connectivity features

Examples of smartphone miniaturization:

- Camera used for colorimetric or fluorescence detection
 - Apps for quantitative analysis
 - Portable attachments acting as spectrometers or microscopes
- This approach enhances accessibility and data sharing.

8. System-on-Chip (SoC) and MEMS Technologies

Micro-Electro-Mechanical Systems (MEMS) combine mechanical elements, sensors, actuators, and electronics on a chip.

Applications include:

- Pressure sensors
- Accelerometers
- Microcantilevers for chemical sensing
- Miniaturized gas chromatographs

SoC integrates multiple electronic components into one chip, reducing device size and increasing performance.

9. Surface Functionalization and Nanostructuring

Nanoscale modifications enhance sensitivity and chemical specificity. Techniques include:

- Self-assembled monolayers (SAMs)
- Metal nanoparticle deposition
- Polymer coatings These

methods improve:

- Selectivity toward target analytes
- Stability of sensors
- Signal

CONCLUSION:

Miniaturized and portable analytical devices represent a transformative advancement in the field of chemical analysis, bridging the gap between traditional laboratory-based instrumentation and real-time on-site testing. The integration of microfluidics, nanotechnology, advanced sensor materials, microelectronics, and smartphone-based platforms has enabled the development of highly compact, efficient, and user-friendly analytical systems. These devices offer significant advantages such as reduced sample volume, rapid analysis, low operational cost, and enhanced portability, making them ideal for applications in environmental monitoring, biomedical diagnostics, food safety assessment, industrial process control, and forensic science.

However, despite these advancements, portable analytical devices still face limitations including sensitivity issues, environmental interference, limited separation efficiency, and dependency on battery life. Continuous research is focused on improving device robustness, analytical accuracy, sensor lifespan, and data processing capabilities through advanced fabrication techniques, nanomaterial enhancement, artificial intelligence integration, and cloud-based interpretation systems.

Overall, the evolution of portable analytical technologies is steadily moving toward creating fully automated, intelligent, and multifunctional point-of-use devices that can deliver laboratory-quality analysis anytime and anywhere. As innovation continues, these devices will play an increasingly vital role in strengthening global health systems, environmental protection, industrial safety, and scientific research.

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