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Microfluidic lab-on-a-chip platforms for environmental monitoring

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KEYWORDS: Microfluidic devices, lab-on-a-chip, environmental monitoring, optical sensor, electrochemical sensor, deployable sensor, miniaturization

HIGHLIGHTS:

- Electrochemical and optical detection-based platforms for environmental monitoring
- Autonomous field deployable systems are described
- Printing technologies for upcoming challenges

ABSTRACT: There is a global concern about the environmental impact of pollutants derived from their widespread use and subsequent persistence in the environment. In this context, attempts to develop novel methods/technologies for detection of pollutants in real-time have attracted much attention. The ever-increasing demand of remote autonomous field deployable analytical systems has become the driving force of microfluidic systems development. Microfluidic lab-on-a-chip (LOC) platforms excel, offering continuous tracking of chemical agents in an integrated miniaturised fashion. Herein, we focus on the latest developments in environmental LOC monitoring devices and provide future perspectives to overcome the challenges that environmental monitoring face using printing technologies.

INTRODUCTION

Microfluidic lab-on-a-chip (LOC) platforms have been extensively studied due to their possibility of replacing a fully equipped conventional laboratory. [1], [2] Since traditional analysis methods consist of multiple steps (*e.g.* sampling, transport, pre-treatment…) and are rather costly and time consuming, the emphasis nowadays is shifted towards the use of remote automated systems in a miniaturised fashion. Well-known advantages of these LOC sensing systems include: compactness, low sample consumption, low-cost production, better overall process control, real-time analysis and a fast response. [3], [4] These characteristics open the possibility of performing *in situ,* real-time measurements. Also, LOC operate in such a manner that sample pre-treatment as well as chemical assay can be performed therein. Their ergonomic and user-friendly design allows LOC to be easily adapted to perform a desired analysis just by simply modifying the pattern of the channels. This makes LOC of particular interest in processes that require multiple analyses at the same time. For instance, a LOC device could be able to continuously analyse pollutants from wastewater serving as an always-on environmental alarm. [5] When combining the aforementioned technology with wireless communication, it becomes a powerful tool with the possibility of remotely modify acquisition parameters as well as enable data transfer.

Therefore, the ever-increasing demand of remote autonomous multiplexed analytical systems make LOC a suitable approach for chemical agents screening in different fields. That said, in the present review we expose the latest developments in environmental LOC monitoring devices (that could determine concentration of contaminants around the maximum level that is allowed in drinking water by the Environmental Protection Agency) and provide future perspective.

ELECTROCHEMICAL

Commonly, electrochemical LOC working principle is based on an electrical signal produced by an interaction between the analyte and the electrode surface. In this section, we will briefly discuss some of the latest electrochemical devices for environmental monitoring that have been proposed by the scientific community.

A smart approach for the detection of inorganic anions (Cl^-, NO_3^-, SO_4^{2-} and NO_2^-) in environmental samples using a microchip electrophoresis system with capacitive coupled contactless conductivity detection (Figure 1Aa) was reported by Freitas *et al.* [6] The device was composed by four electrodes; two of them were used as excitation/receiver and the other two were used as reference electrodes to minimize the stray capacitance. Inorganic anions were successfully separated within 60 s using a mixture of lactic acid (30 mM) and L-histidine (15 mM), and $Cr_2O_7^{2-}$ as internal standard (Figure 1Ab). Once selectivity and sensitivity were optimised, the device presented a linear behaviour from 0 to 120 µM for Cl^-, NO_3^- and NO_2^-, and from 0 to 60 µM for SO_4^{2-}. The authors explored the feasibility of the presented device in real environmental samples. First, an artificial spiked-environmental sample was used to check the spontaneous oxidation of ammonium to nitrite and a further oxidation to nitrate during twelve weeks. After the concept was proven to be suitable for the simulated environment, authors proceeded with the screening of nitrogen species in an aquarium containing *Danio rerio* fishes. During eight weeks, they were able to monitor an absence of nitrite, suggesting the direct oxidation of ammonium to nitrate. These results demonstrate the feasibility of the device for *in situ*, real-time inorganic anions analyses.

An interesting environmental application for LOC platforms was reported by Calvo-López *et al.* [7] As the total charge of an aerospace ship is limited, recycling of resources like water is crucial, and thereby tracking the quality of water. The authors reported a bipotentiometric (NO_3^- and K^+) LOC system for water monitoring in manned space flights (Figure 1B). The LOC system was constructed using low temperature co-fired ceramics with integrated potassium/nitrate ion-selective electrodes and a silver paste-based pseudo-reference electrode. Polyvinyl chloride-based membranes containing well-known ionophores for nitrate and potassium ions (tetraoctylammonium nitrate and valinomycin, respectively) were used as recognition elements. Authors studied the behaviour of the response towards the most common interferences (Na^+, NH_4^+, Ca^{2+}, Mg^{2+}, HCO_3^- and Cl^-), demonstrating no significant interference at the expected concentrations on these particular ions at environmental conditions. Moreover, authors tested the performance of their device with recycling water provided by the Antarctic Concordia station and compared their results with the ones obtained by optical emission spectrometry (K^+) and ionic chromatography (NO_3^-). While potassium ion determination gave outstanding results, nitrate ion determination selectivity was outperformed by chloride ion at concentration surrounding the limit of detection. Moreover, authors demonstrated the feasibility of low temperature co-fired ceramics-based LOC for multiplexed ionic determination in recycling water with potential applicability in manned space flights.

The crucial point as far as toxicity is concerned is the understanding of the chemical changes of

pollutants produced by external factors. A LOC electrochemical cell with boron-doped diamond (BDD) electrodes (Figure 1Ca) for metabolism studies of common environmental xenobiotics and their respective protein adduct formation was developed by Floris *et al.* [8] One of the main features of microfluidics systems is the laminar flow behaviour of the liquid which slow the final mixing purpose of the device. To overcome that feature, the authors developed a passive gradient rotation micromixer (Figure 1Cb) reducing the mixing time to milliseconds. To prove the potential of the device, 1-hydroxypyrene was chosen as a common polycyclic aromatic carbon produced by the non-complete combustion of organic matter. To produce the corresponding oxidized molecules of 1-hydroxypyrene, a 1.2 V potential was applied by the BDD electrode. Then the xenobiotics obtained were analysed by a mass spectrometer directly coupled to the LOC system. The oxidized molecules were allowed to react with two different proteins, β-lactoglobulin A and haemoglobin showing the formation of the adducts and therefore affecting their biological capabilities. To conclude, authors demonstrate the potential of LOC systems for understanding the toxicity of common environmental xenobiotics in a fast and cheap manner.

Along the present review, electrochemical LOC devices have been presented as portable sensing platforms. However, Medina-Sánchez *et al*. [9] step forward designing a set of microfluidic platforms for atrazine sensing and degradation based on BDD electrodes (Figure 1D). Smartly, selection of BDD electrodes was due to their low adsorption capacity towards organic pollutants, inert nature and higher O_2 overvoltage making them an appealing option for both, sensing and degradation in flow systems. On the one hand, the working principle of the sensor relied on a competitive assay between horseradish peroxidase-labelled atrazine and free atrazine for anti-atrazine antibody immobilised onto magnetic beads. On the other hand, simultaneous degradation of atrazine takes place in a different microfluidic platform. The degradation is based on the production of superoxide radicals when a current is applied to the BDD electrode, being those radicals able to breakdown atrazine into cyanuric acid, which is a considerable less toxic molecule. Overall, authors presented a LOC which shows an impressive limit of detection of 1 nM of atrazine whilst degrading over a 97% of atrazine (30 nM).

Another approach that includes sensing and degradation was reported by the same research group. [10] The contaminants studied were polybrominated diphenyl ethers (PBDE), a family of flame retardants that has become a global threat. Once again, the working principle of the sensor relied on a competitive assay between free PBDE and horseradish peroxidase-labelled PBDE for anti-PBDE immobilised onto magnetic beads. The system consisted of three consecutive microfluidic platforms each one with a defined function (Figure 1 E). In the first platform, the immunoreaction takes place through a simple passive mixer. Then, detection happens in the second chip by measuring the reduction of 3-aminophenoxazone (produced by the oxidation of o-aminophenol) using square wave anodic stripping voltammetry. With the use of this electrochemical technique the authors were able to achieve an impressive limit of detection of 0.018 ppb. Finally, in the third chip PBDE is adsorbed onto a composite containing reduced graphene oxide thanks to π-π stacking interactions. Furthermore, authors demonstrate the potential of their system for real measurement of spiked seawater samples.

Gonzalez-Rivera *et al.* [11] developed a flow-injection LOC platform for determination of phenolic compounds by amperometry (Figure 1F). Authors extensively studied the immobilization of lacasse by potential step chronoamperometry. To demonstrate the successful immobilization, electrochemical impedance and cyclic voltammetry were carried out before and after immobilization. The increase of the charge

transfer resistance and the current decrease of oxidation and reduction peaks ensured a successful approach for electrochemical immobilization of enzymes. Once the presence of laccase in the working electrode was proved, authors studied several parameters (pH, temperature, potential applied and injection rate) that would affect the electrochemical performance of the LOC. To prove the performance of this device (2,2-azino-bis(3-ethylbenzothiazoline-6) sulphonic acid) and syringaldazine were chosen as phenolic compounds achieving a limit of detection of 0.149 and 10 µM, respectively. Furthermore, this LOC platforms showed good stability up to 10 days. To conclude, this microfluidic biosensor showed its potential for monitoring of phenolic compounds.

OPTICAL

So far, several electrochemical strategies have been presented for environmental screening purposes. Otherwise, optical devices are well-known for their simplicity and low-cost. Commonly, optical LOC rely on a colour change given by an interaction or reaction between the pollutant (analyte) and a chemical. Although most of the microfluidic devices shown so far are made of polymeric materials, paper-based microfluidic systems will excel as platforms for simple colorimetric reactions.

Cardoso *et al.* [12] reported the use of disposable microfluidic paper-based device for colorimetric detection of nitrite ion in environmental samples. The change of colour (from colourless to strong pink) in the presence of nitrite was based on the well-known Griess reaction. The device itself consists of eight star-like paths, in which three of them were used as controls (1-3) and five of them as detection areas (4-8) for standards or samples (Figure 2Aa). Although the presence of nitrite ion was easily discernible by naked eye, the use of a common office scanner and digital photo software for colorimetric calibration was explored. A linear response between 0 and 100 µM (Figure 2Ab) with a limit of detection of 11.3 µM. Authors determined the nitrite ion concentration in a river and compared it with the one quantified by spectrophotometry in batch, finding no significant difference at a confidence level of 95%. Therefore, a cheap substrate was demonstrated to be a powerful tool for *in situ* colorimetric determination with environmental sensing purposes.

Another paper-based LOC system was developed by Kim *et al.* [13] The wax-printed LOC platform was designed for fast microorganism detection in environmental samples using *Escherichia coli (E. coli*) as a proof of concept. The sensor working principle relied on the combination of catalase and Fenton's reactions for an easy colorimetric detection. First, a solution containing *E. coli* is mixed with hydrogen peroxide. Then, the remaining hydrogen peroxide reacts with iron (II) compound at the paper-based LOC chambers and a change of colour from pale yellow to brown occurs. Therefore, brightness increases as the microorganism concentration increases (Figure 2Ba). The authors also designed a simple 3D-printed holder for fully integration into a hand-held LOC device for field detection without the need of expensive equipment (Figure 2Bb). Finally, the device performance was tested on several real environmental samples (mineral water, drinking water, humidifier water…) showing good correlation with their calibration for an *E. coli*-simulated environment. As a result of the paper-based LOC performance, authors conclude that it could find uses in real environmental contexts for *in situ* measurements.

Another interesting LOC platform for microorganism detection was studied by Huang *et al.*[14] The LOC platform is coupled with a multi-angle laser scattering system which could acquire scattering patterns of single molecules (Figure 2C). The LOC itself is composed of one-channel with a stretching (called interrogation zone) at which analysis are performed. To process the complex data acquired, a pattern recognition

method and support-vector-machine algorithm. Authors optimized the configuration of the LOC using polystyrene microparticles to accomplish high signal to noise ratio. Afterwards, authors tested the device using several waterborne microorganisms (*C. parvum, G. lamblia and E. coli*) over silt. The results agreed to count/identification using a standard optical microscope. Overall, this identification strategy constitutes a game changer in the label-free identification of microorganism in water.

Cate *et al.* [15] reported a different optical strategy for heavy metal ion detection, in which the quantification was made by travelled distance (same principle as mercury thermometers) instead of colour intensity (Figure 2Da). Authors produced a simple multiplexed paper-based LOC with the capability to determine Fe (20-1300 mg/L, Ni (100-1100 mg/L) and Cu (100-1300 mg/L) concentrations simultaneously in ~40 min (Figure 2Db). The device itself was fully constructed by the use of printing techniques. The channels were delimited by wax printing while the reagents were inkjet-printed by a common modified office printer. When the sample is drop-casted onto the system, it flows through the channels reacting with the colorimetric reagents (4,7-diphenyl-1-1,10-phenanthroline, dimethylglyoxime and dithiooxamide for Fe, Ni and Cu, respectively) forming a coloured precipitate. The efficiency of the device was tested with certified stainless steel welding powder and further compared with the company quantification values, showing a significant good performance. Truly, the concentration ranges measured with this system heavily exceeds the concentrations establish by the legislation and therefore further development to decrease the detection range should be performed. Nonetheless, the fact that this new strategy could overcome the need for external readers as distance can be easily determined by naked-eye will represent an important advance for on-field applications.

Bell *et al.* [16] developed a LOC device that combines droplet-based microfluidic system with gated indicator for Hg^{2+} detection. The gated indicator principle is based on the release of a chemical embedded onto a scaffold that can be easily quantified. Authors designed a polyethylene glycosylated boron dipyrromethene (indicator)-loaded silica nanoparticles (scaffold) with a squaraine acting as gate. Upon reaction of Hg^{2+} the gate is "opened" releasing the indicator, which is directly proportional to the heavy metal concentration (Figure 2E). The use of droplet-based microfluidic system was chosen to take advantage of the microreactor-like behaviour. Therefore, Hg^{2+} recognition and indicator release takes place in the water drop. Then, the dye is extracted into an organic phase (CH_2Cl_2, carrier) in order to avoid the readout interference coming from the indicator that remains in the nanoparticles. Overall, authors were able to detect Hg^{2+} ions in water with a limit of detection of 20 ppt, which is 50 times less than the maximum amount of Hg^{2+} allowed in drinking water.

A nanoceria-coated paper device for determination of organophosphate was reported by Nouanthavong. [17] The formation of H_2O_2 by two consecutive enzymatic reactions is used to oxidize Ce^{3+} to Ce^{4+} giving a change of colour (colourless to yellow, Figure 2F). The first enzymatic reaction (by acetylcholinesterase) uses acetylcholine as substrate to produce choline, while the second enzymatic reaction (by choline oxidase) produce H_2O_2 from choline. Generally, the sensor relied on an inhibition of acetylcholinesterase in the presence of organophosphate compounds, which in turns decrease the intensity of yellow. The sensor could achieve impressive limits of detections of 18 and 5.3 $ng{\cdot}mL^{-1}$ for methyl-paraoxon and chlorpyrifos-oxon, respectively. Furthermore, authors demonstrate the potential of the device in spiked cabbage and green mussel and compare the values obtain with chromatography couplet to a mass spectrometer showing no significant

differences. Therefore, the potential of this system is for accurate and simple organophosphate detection is highlighted.

AUTONOMOUS FIELD DEPLOYABLE DEVICES

Tracking of chemical compounds in the environment remains challenging due to the full integration of the sensing system in an autonomous way. It must be taken into account that a fully integrated device must provide storage containers, power supply and electronics for process control and data transfer.

That said, Perez de Vargas *et al.* [18] developed an autonomous colorimetric LOC prototype for pH sensing. The device consists of a battery, electronics, reagents and waste containers and pumps for microfluidic management (Figure 3A) Authors explored the use of different combination of dyes in order to extend the pH detection range, in which a mixture of phenol red, chlorophenol red and bromophenol blue showed the broadest range (from 4 to 9). Repeatability tests were performed presenting an overall relative standard deviation of 2.82%, hence ensuring the capability of the system for analyses along time. Moreover, authors estimated the pH of effluent, drinking water, surface water and buffer (pH=6) and compared the values obtained with the ones analysed by an external company showing an overall relative error of 5.96%. Lastly, reagents presented stability during 8 months confirming the feasibility for system deployment in the environment.

One of the main problems in deployable devices is the use of batteries as power supplies, which are heavy, heat up affecting the measurements and do not last for long periods of time. To solve that problem, Höfflin *et al.* [19] reported a technical innovation; a wireless power transfer based on inductively coupled coils, to a spinning disk that could be easily integrated in a sensing rotating platform (Figure 3B). The system itself is able to wireless supply 5 V for both, Arduino microcontroller and sensors and actuators opening the possibility of designing more complex field deployable LOC devices. Authors strongly believe that this kind of power supply will find numerous applications in field deployable devices in the near future.

CHALLENGES

Finally, in this section we will describe the challenges that environmental monitoring still faces and discuss the feasibility of printing technologies to overcome them (Figure 4).

One of the features that limits the lifetime of a system in the environment is the stability of the material that is it made of. Polymeric materials, which excel because of their chemical stability have been exploited as the scaffold to contain the sensors and actuators. However, the metallic nature of the electronics involved is the critical point that delimits the performance of the device. Deployable systems undergo oxidant conditions as they are placed in water, which in turns means the analytical performance of the device will be affected after a period. Metallic materials could be easily replaced for conductive polymers like polyaniline or Poly(3,4-ethylenedioxythiophene) which can be directly printed on almost any desired surface.

Another important factor to take into account is the stability of the reactants involved in the analyses. Typically, reactants used in optical assay contain aromatic rings. Upon severe oxidation conditions this rings may breakdown in to colourless chemicals decreasing the sensitivity of the assay. On the other hand, electrochemical assays commonly relied on the capability of a biomolecule to interact with an analyte. The use of biomolecules such as antibodies, aptamers or enzymes must be avoided as their bioactivity decreases drastically due to their low stability in environmental conditions.

As mentioned previously, an important problem to solve in deployable devices is the use of batteries as power supplies. Although in this

review we have exposed a technology based on inductively coupled coils for wireless power transfer, this technology still requires an external power supply. A smart alternative could be the use of renewable energies in which energy harvested from external factors such as sunlight or hydrodynamics would supply the device. Scientists across the globe have made a lot of effort to develop affordable photovoltaic cells that would be able to provide the energy expenses of an autonomous system. Moreover, inkjet printing has been widely used as the main technology to produce low-cost fuel cells as they consist on multiple stacked layers.

Another big challenge associated with any analytical assay is the treatment of interferences. In the case of environmental assays, highly complex matrices commonly lead to a wide variety of interferences, which could not only affect the read-out value, but also the lifetime of the system. Over the year, different manners to discriminate one analyte upon the matrix with the use of highly selective molecules have been proposed. Although, some interferences in the read-out value could be solved using selective molecules there is still another problem in real environmental samples. Among others, environmental samples usually contain colloidal particles, which could affect both, optical, and electrochemical-based analyses. On the one hand, particles provoke light scattering, which will slightly change the concentration value of the analyte. On the other hand, particles could scratch the external surface of the electrodes used for the assay. A simple and low-cost solution could be the use of a revolver-like filtration system enclosed within the device. This filtration system will be able to solve the problems that small particles cause. Furthermore, when the sieve clogged, the filtration system will spin and a new sieve will be placed. This smart strategy could be easily implemented taking advantage of 3D printing and will increase the lifetime of the system.

Technology used so far to produce field deployable devices is complex and costly. Printing technologies have been overwhelmingly implemented for the production of low-cost systems for analytical purposes. Although these printing technologies have been exploited for the production of point-of-care devices and wearable electronics, environmental application still need to be harnessed.

CONCLUSIONS AND FUTURE PERSPECTIVE

Throughout the present review, the potential of LOC systems with different detection principles for environmental application has been discussed. The main advantage of these devices presented so far is the capability of integrating in a small space all processes involved in the analysis. This fact, allows the reduction of operational, production and reactants costs as long as offers the possibility to perform analyses in an autonomous way.

We strongly believe that unaddressed technological gaps could be filled in the near future with emerging technologies such as three-dimensional printing and inkjet printing. Printing technologies will not only solve the problems that environmental monitoring face, but also will become the standard technology to produce autonomous full deployable systems at a low cost. Moreover, wireless connectivity will be crucial to overcome the challenges autonomous deployable devices face. Overall, LOC sensing systems will excel as promising miniaturised platforms for in situ and real-time monitoring of pollutants. Despite in this review we emphasised the LOC systems for environmental applications, they could also find uses in biomedical and biotechnological fields.

ABBREVIATIONS

BDD, Boron-doped diamond; LOC, Microfluidic lab on a chip; PBDE, polybrominated diphenyl ethers.

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Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

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Microfluidic lab-on-a-chip platforms for environmental monitoring

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Figure caption

Figure 1. A: a) Scheme of the microchip electrophoresis device for inorganic anions quantification. b) Electropherograms showing both, separation and detection of diverse ions Cl^-, NO_3^-, SO_4^{2-} and NO_2^- in three kind of real samples: aquarium (black), biofertilizer (red) and river (blue), using $Cr_2O_7^{2-}$ as internal standard. B: Concept representation of the presented bipotentiometric LOC (NO_3^- and K^+) for water monitoring in manned space flights. C: a) Image of the LOC device for xenobiotic metabolites monitoring. b) Proposed passive gradient rotation micromixer. D: LOC platform scheme for detection and degradation of atrazine. a) Degradation microfluidic platform. b) Microfluidic mixer for magneto-enzyme immunoassay. c) Detection microfluidic platform with a platinum nanoparticles-modified BDD electrode as the detector. d) Mechanism proposed for the atrazine degradation via superoxide radicals; from atrazine (left) to cyanuric acid (right). E: Assembled device containing three consecutive LOC for immunoreaction, detection and removal of PBDE. F: Diagram of the microfluidic biosensor system layer by layer and its set-up.

Figure 2. A: a) Microfluidic paper-based analytical device used for nitrite ion determination through the modified Griess reaction. (1-3) and (4-8) cavities correspond to control and detection areas for standards or samples, respectively. b) Calibration curve obtained for nitrite ion from 0 to 100 μM. B: a) Colorimetric assay with paper-based LOC for five different E. coli concentrations (from 0 to 8.77x108 cells/mL). b) 3D-printed paper LOC holder design to prevent sample adhesion to the surface. C: Schematic configuration of the LOC coupled with coupled with a multi-angle laser scattering. D: a) Distance-based multiplexed device for Ni, Fe and Cu detection. b) Calibration curves, for Ni, Fe and Cu, obtained using the multiplexed device. E: Schematic representation and reaction of 2,4-bis(4-dialkylaminophenyl)-3-hydroxy-4-alkylsulfanylcyclobut-2-enone (red sphere) with Hg^{2+} (green sphere) releasing polyethylene glycosylated boron dipyrromethene indicator (yellow sphere) showing the gated working principle of the device for Hg^{2+} ion determination. F: Conceptual scheme of the

reactions involved in the determination of organophosphates by two stage enzymatic reactions.

Figure 3. A: Schematic representation of the portable prototype for pH sensing; assembled view, internal view and pumps (from left to right). B: 3D representation of the full integrated lab-on-a-disk proposed device with the inductively coupled coil as power facility and all steps included on a measurement process.

Figure 4. Scheme representing the possible solutions that we propose for the challenges environmental monitoring face.

Figure 1

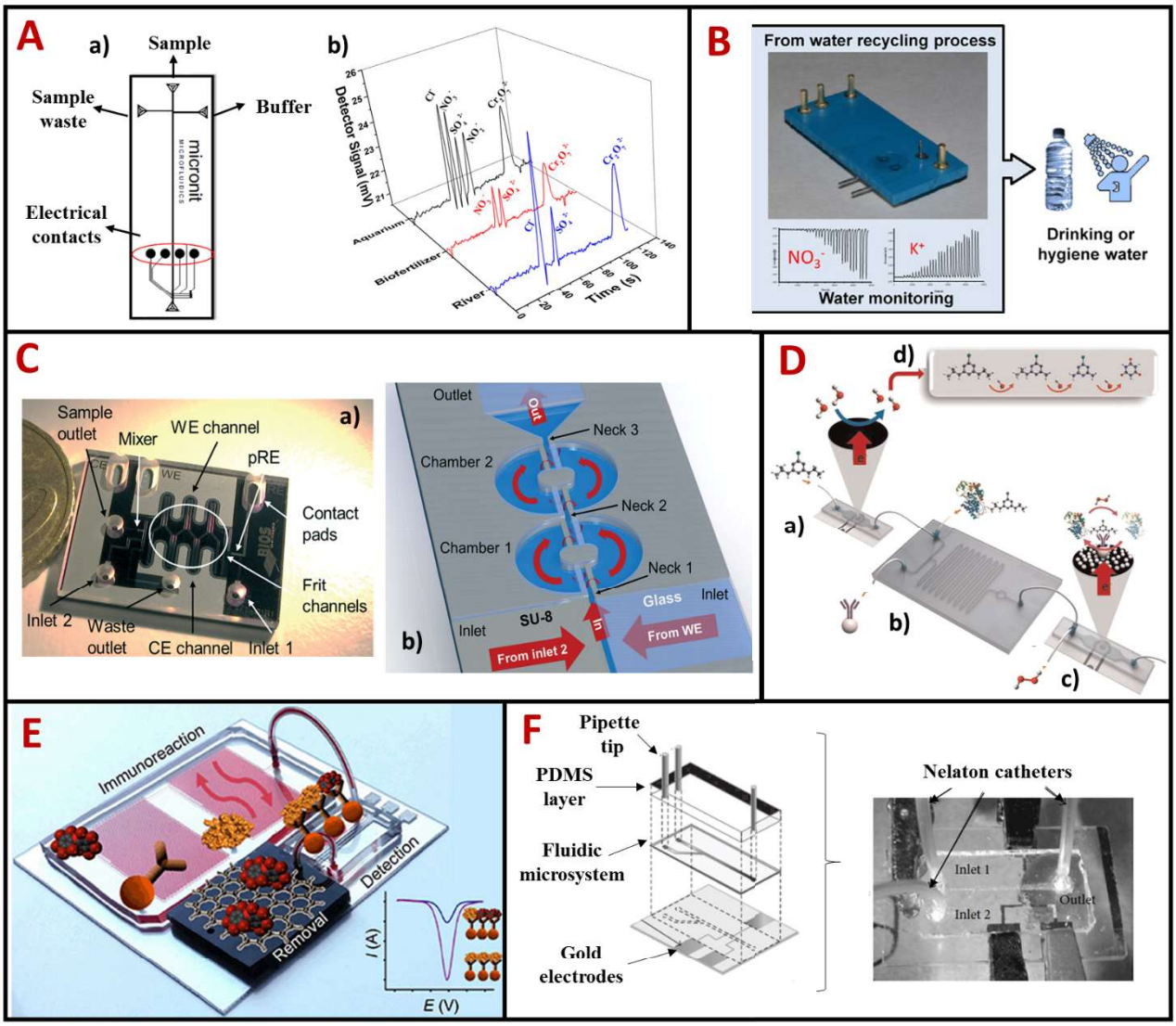

A
a)
Sample
Sample waste
Buffer
Electrical contacts
micronit
b)
Detector Signal (mV)
Aquarium
Biofertilizer
River
Time (s)
B
From water recycling process
Water monitoring
Drinking or hygiene water
C
a)
Sample outlet
Mixer
WE channel
pRE
Contact pads
Frit channels
Inlet 2
Waste outlet
CE channel
Inlet 1
b)
Outlet
Out
Neck 3
Chamber 2
Neck 2
Chamber 1
Neck 1
Glass
Inlet
SU-8
From inlet 2
From WE
D
d)
a)
b)
c)
E
Immunoreaction
Detection
Removal
I (A)
E (V)
F
Pipette tip
PDMS layer
Fluidic microsystem
Gold electrodes
Nelaton catheters
Inlet 1
Inlet 2
Outlet

Figure 2

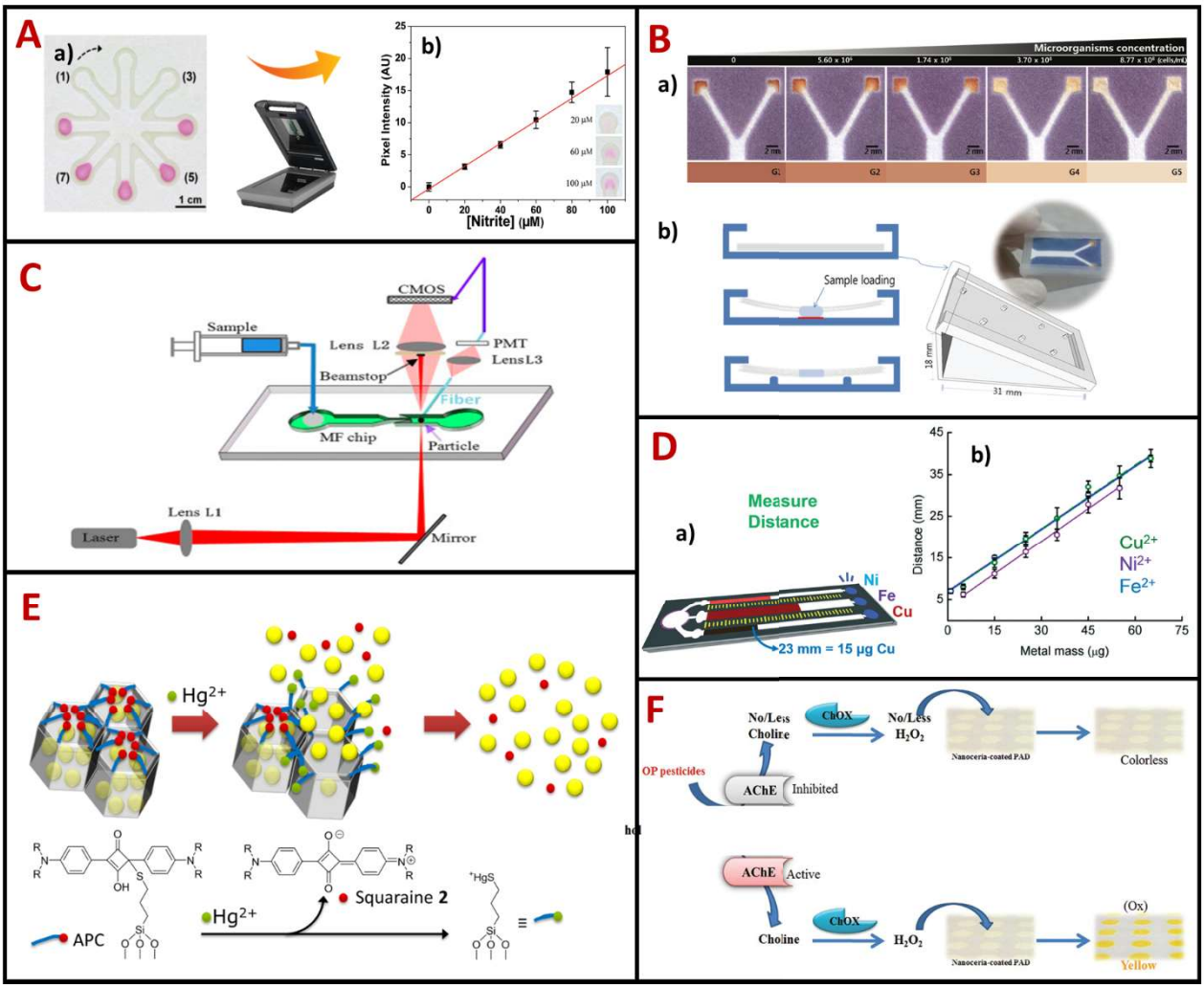

A
a)
(1)
(3)
(7)
(5)
1 cm
b)
Pixel Intensity (AU)
[Nitrite] (μM)
20 μM
60 μM
100 μM
B
a)
Microorganisms concentration
G1
G2
G3
G4
G5
b)
Sample loading
18 mm
31 mm
C
CMOS
Sample
Lens L2
PMT
Lens L3
Beamstop
Fiber
MF chip
Particle
Lens L1
Laser
Mirror
D
a)
Measure
Distance
Ni
Fe
Cu
23 mm = 15 μg Cu
b)
Distance (mm)
Metal mass (μg)
Cu2+
Ni2+
Fe2+
E
Hg2+
APC
Squaraine 2
F
No/Less
Choline
ChOX
No/Less
H2O2
Nanoceria-coated PAD
Colorless
OP pesticides
AChE
Inhibited
AChE
Active
Choline
ChOX
H2O2
Nanoceria-coated PAD
(Ox)
Yellow

Figure 3

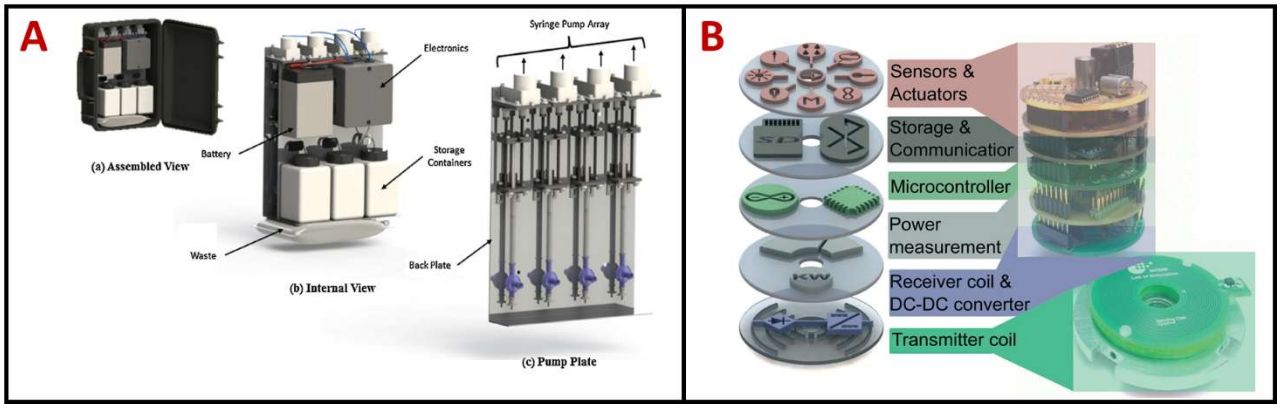
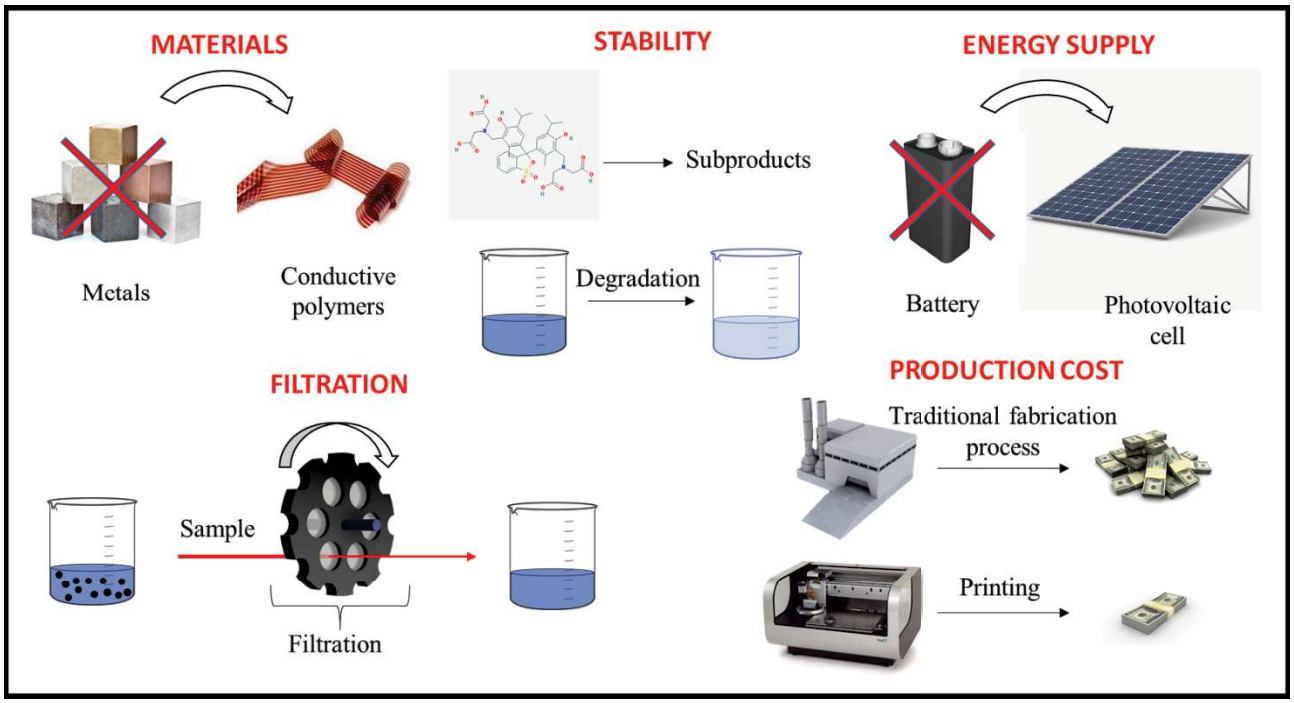

A
Electronics
Syringe Pump Array
Battery
Storage Containers
(a) Assembled View
Waste
Back Plate
(b) Internal View
(c) Pump Plate
B
Sensors & Actuators
Storage & Communicatior
Microcontroller
Power measurement
Receiver coil & DC-DC converter
Transmitter coil

Figure 4


MATERIALS
Metals
Conductive polymers
STABILITY
Subproducts
Degradation
ENERGY SUPPLY
Battery
Photovoltaic cell
FILTRATION
Sample
Filtration
PRODUCTION COST
Traditional fabrication process
Printing