Optofluidic opportunities in global health, food, water and energy

Yih-Fan Chen, Li Jiang, Matthew Mancuso, Aadhar Jain, Vlad Oncescu and David Erickson

Received 10th April 2012, Accepted 5th June 2012
DOI: 10.1039/c2nr30859b

Optofluidics is a rapidly advancing field that utilizes the integration of optics and microfluidics to provide a number of novel functionalities in microsystems. In this review, we discuss how this approach can potentially be applied to address some of the greatest challenges facing both the developing and developed world, including healthcare, food shortages, malnutrition, water purification, and energy. While medical diagnostics has received most of the attention to date, here we show that some other areas can also potentially benefit from optofluidic technology. Whenever possible we briefly describe how microsystems are currently used to address these problems and then explain why and how optofluidics can provide better solutions. The focus of the article is on the applications of optofluidic techniques in low-resource settings, but we also emphasize that some of these techniques, such as those related to food production, food safety assessment, nutrition monitoring, and energy production, could be very useful in well-developed areas as well.

1. Introduction

Out of the 7 billion people alive today, approximately 5.7 billion of them live in developing nations. Over one billion of these people live on less than $1.25 a day, many of whom do not have access to basic goods and technologies including clean water, food, basic healthcare, and energy. In the next century, world population is expected to increase by another 3 billion people, almost exclusively in developing regions, leading to an additional strain on resources.

The unequal distribution of wealth and resources along with the growing population pose significant challenges to providing...
safe and adequate water, food, and other resources for people around the world, in both developing and developed countries. With a large number of cases of foodborne illness occurring in developing and developed countries, nearly 900 million people living with unimproved water sources, and 800 million people suffering from hunger and malnutrition, the magnitudes of these problems are huge. To address these challenges, new technologies are urgently needed that can improve the performance and reduce the cost of food safety assessment, agricultural production, water purification and desalination, and nutrition monitoring. In addition, considering the enormous burden caused by infectious diseases in developing countries, it is also critical to develop portable, low-cost, easy-to-use medical diagnostic devices to prevent and treat diseases in low-resource settings more effectively. Moreover, to reduce the negative environmental impact of electricity generation, technologies related to the production of renewable energy, such as solar power and biofuel, are important.

In developing countries, due to the lack of necessary laboratory infrastructure and well-trained professionals, technologies that are developed to address the challenges mentioned above should usually come in forms of low-cost, integrated, autonomous microsystems, some of which may even be powered by solar energy since access to power is often limited.

Optofluidics, an interdisciplinary research field investigating the integration of optics and fluids, has been rapidly developed in recent years to provide unique techniques and tools for biological/chemical sensing and analysis, optical manipulation, energy, and tunable or reconfigurable photonic systems. Although optics has long been integrated with fluids on various microfluidic devices, precise simultaneous control of their interactions at small scales has only recently been studied and utilized to develop devices that have better adaptability, tunability, reconfigurability, or have unique functions not available in traditional microsystems. With light manipulation and fluid handling capabilities at micro and nano scales, optofluidic devices have the potential to be important platforms to tackle challenges in global health, energy, and a number of other fields. Additionally, recent work has shown methods of coupling solar light directly into photonic devices, enabling the creation of solar powered optofluidic devices ideal for use in infrastructure and resource scarce settings.

Matthew Mancuso is a fourth year PhD candidate and National Science Foundation Graduate Research Fellow working under the supervision of Professor David Erickson at Cornell University. His dissertation work focuses on the detection of infectious cancers, such as Kaposi’s sarcoma, in the developing world. He received his Bachelors of Engineering cum laude from the Department of Biomedical Engineering at Stony Brook University in May 2009.

Aadhar Jain received his Bachelor of Technology in Mechanical Engineering from Indian Institute of Technology (IIT) Kanpur. He is currently a fourth year PhD student in Mechanical and Aerospace Engineering at Cornell University and working under the supervision of Professor David Erickson. His research consists of developing soft photonic devices for cell studies and solar driven microfluidics for applications in water conservation and production.

Vlad Oncescu is currently a fourth year graduate student in the Department of Mechanical Engineering at Cornell University. His research interests include nanoscale energy conversion and the development of autonomous implantable devices for medical diagnostics and treatment. Currently he is developing non-enzymatic glucose fuel cells for powering long-term implantable devices. He has previously received a B.Eng. in Mechanical Engineering from McGill University in 2009.

Prof. David Erickson is a Professor of Mechanical Engineering at Cornell University. In recent years, Dr Erickson has received the DARPA-MTO Young Faculty Award, the NSF CAREER Award, and the Department of Energy Early Career Award. In 2011 he was awarded the Presidential Early Career Award for Scientist and Engineers (PECASE) under President Obama. Prof. Erickson is the Co-Founder of Optofluidics, Inc., which was named Philadelphia life-sciences startup of the year in 2012.
In this review, we introduce readers to the possibilities of utilizing optofluidic technologies to help find solutions to some of the most important challenges facing the world (Fig. 1). In Section 2, we discuss how optofluidic technologies can be used to provide accurate and affordable medical diagnostics. In Section 3, we explore the possible ways that optofluidics could be applied to ensure food safety and quality, and to provide better health monitoring for individuals as well as animals and plants. In Section 4, water sanitation and desalination technologies based on optofluidics are reviewed. Finally, in Section 5 we briefly describe the possibilities for applying optofluidics to the field of energy.

2. Optofluidics in medical diagnostics: advances in detection, sample processing, and reconfiguration

In the developing world there are over 225 million malaria cases per year, approximately 9 million new tuberculosis cases, and over 2 million people newly infected with HIV as well as millions more suffering from many other diseases. Due to a lack of medical expertise, infrastructure, and resources, proper diagnosis of disease is often unavailable to those who need it most. Given that biosensing devices, especially those based on traditional microfluidics, have been reviewed in a few articles recently, here we only give a brief review of optofluidic detection technologies and focus mainly on how optofluidics can be used to create the other components of diagnostic systems, namely those involved in on-chip imaging, sample processing, and flow manipulation. By combining existing microfluidic technologies with newly developed optofluidic components and functionalities, we explain how it could be possible to develop optofluidic diagnostic systems that medical professionals can use in the developing world to help people afflicted with various diseases.

2.1. Optofluidic detection and sample interrogation

Researchers have created a number of optofluidic devices by utilizing waveguiding technology and microfluidics to simultaneously localize optical fields and fluid flows to small volumes. Examples of these devices have been used to create biosensors, molecular traps, and devices for transporting micrometer and nanometer sized objects. While many of these devices require a significant amount of nanofabrication and may not yet be ready for use in the developing world, a number of recent works have been aimed at creating cheaper and more suitable technologies, including those based on polymers. One of the earliest works on polymer devices was completed by the Guo group from the University of Michigan in 2002. Since then, his group has demonstrated that these devices could be fabricated into high Q-factor ring resonators, and have used them for biosensing applications. In addition, other groups have attempted to maximize interactions between the optical and microfluidic components of these polymer devices by creating porous waveguide structures and ring resonators, or soft gel waveguides. Other groups have used polymers to create photonic crystal structures made of polymers and used them in biosensing applications. In one example, Mathias et al. show how polymer photonic crystals can be used to detect tumor necrosis factor-alpha (TNF-α) at concentrations as low as 1.6 pg/ml. These devices capitalize on the advantages of polymer devices, i.e. their low-cost materials and fabrication, and provide additional advantages by creating material constructs that increase light–matter interactions not easily made in silicon devices.

Recently, novel optofluidic technologies such as anti-resonant reflecting optical waveguides (ARROWs) and rolled-up optofluidic ring resonators (RU-OFRRs) have shown the capability to confine and analyze samples on an individual cell.
basis. These new techniques demonstrate the high precision and controllability of optofluidics for bioanalysis and the potential to detect trace amounts of pathogens in samples. A second group of devices exists that seeks to integrate plasmonic technologies with microfluidics. Since surface plasmons excited on the surface of metal films are extremely sensitive to the surrounding environment, many plasmonic-based biosensors have been developed in recent years for label-free biosensing. While a number of devices are already commercially available, many of them do not meet the cost requirements or simple operability required to be used in resource poor settings. In recent work, a number of groups have improved upon these previous devices, creating systems more applicable to developing countries. One recent example came from Yanik et al. in which plasmonic Fano resonances were used to identify protein monolayers through colorimetric changes visible to the naked eye.

Gold nanoparticles have also received much attention in the last decade for their use in sandwich-based antigen and DNA detections that rely on local surface plasmon resonance (SPR) shifts, as well as silver-deposition enhanced detection assays that resemble enzyme-linked immunosorbent assays (ELISA). The latter detection schemes have been used to identify both oligonucleotide and protein based targets in enzyme-linked immunosorbent assays based on gold nanoparticles, and silver aggregates can be formed around the gold up to sizes that the naked eye and cameras can detect the ligand’s presence. Recently, Chin et al. used this signal amplification technique in their point-of-care device made of injection-molded plastic. They tested the performance of the assay, which is capable of replicating all steps of ELISA at a lower cost, in the diagnosis of HIV and syphilis in Africa (Fig. 2). In addition, Fu et al. have applied a signal amplification technique to paper microfluidic systems by using a gold-deposition instead of silver. Both of these recent examples demonstrate methods of creating devices that can operate almost autonomously without the need for costly infrastructure.

2.2. Optofluidic and cell phone-based imaging

Optical microscopy, which has the ability to provide quantitative and specific diagnosis of live infections, remains the main diagnostic method for some of the most deadly infectious diseases such as malaria and tuberculosis in the developing world. The high costs, bulky size of the instruments, the need for regular maintenance, and the need for well-trained personnel, however, make microscope-based diagnostic methods difficult to widely implement in low-resource settings. Recently, though, optofluidic imaging devices have addressed many of these problems and can be the low-cost, portable alternatives to traditional optical microscopes. The Yang group, for instance, developed optofluidic microscopes that utilize a series of small apertures instead of lenses or other bulky optical components to scan samples such as Caenorhabditis elegans, a free-living roundworm, and cells flowing in a microfluidic channel. The resolution of aperture-based optofluidic microscopy is limited by the aperture size and is 0.8 μm for the demonstrated device. Recently, a pixel super-resolution algorithm was implemented by the same group on optofluidic microscopes to eliminate the need for apertures and to enable imaging samples with sub-pixel resolution. The color imaging capability on optofluidic microscopes, which was demonstrated by imaging red blood cells infected with a type of harmful malaria parasites, Plasmodium falciparum, was achieved by utilizing sequential red-green-blue illumination. Later, an array of Fresnel zone plates was patterned on a metal layer on the top of a microfluidic channel that has a filter-coated CMOS sensor as the channel floor to form optofluidic microscopes capable of fluorescence microscopy, one of the most sensitive diagnostic methods.

Besides the optofluidic microscopes described above, cell phone-based imaging and diagnostic platforms as well as portable lens-free holographic microscopes have also been developed for global health applications. Breslauer et al. developed a microscope attachment consisting of a microscope objective, an eyepiece, and few lenses and filters for cell phones equipped with cameras to provide bright field and fluorescence imaging capabilities. The Ozcan group later demonstrated an optofluidic imaging platform in which optofluidic waveguides were used both to deliver fluorescently labeled cells over a CMOS sensor of a cell phone and to guide the excitation light for fluorescence microscopy and flow cytometry (Fig. 3). Cell phones could later process the images to determine the density of cells or other particles in the sample solution. In addition, digital in-line holography techniques were applied to create portable lens-free microscopes capable of producing two-dimensional or three-dimensional microscopic images without using any lasers or bulky optical/mechanical components. Speckle noise and multiple-reflection interference effects were reduced by using a light emitting diode (LED), a partially spatially and temporally coherent light source, rather than lasers for illumination. Wide field microscopy, which is important for high throughput diagnosis, was achieved by utilizing a specially designed holographic

Fig. 2 A point-of-care device capable of detecting HIV and syphilis using just 1 μl of unprocessed whole blood. (a–c) Images of the device. (d) Reagents are loaded into a tube and then pulled through the device by a vacuum generated by a disposable syringe. (e) Silver enhanced detection scheme. (f) The detector readout during a 20 minute sample detection of syphilis positive HIV negative sample. Reproduced with permission from ref. 21. Copyright 2011 Nature Publishing Group.

4842 | Nanoscale, 2012, 4, 4839–4857
The ability to precisely manipulate fluid flows in microfluidic environments is critical to perform operations such as sample mixing, separation, concentration, filtration, and transport required for advanced diagnostics. In microfluidic devices demonstrated so far, continuous liquid flows are usually driven by pressure, capillary forces, or electrokinetic effects, and droplets are usually driven by electrowetting-on-dielectric (EWOD),70 dielectrophoresis (DEP),71 or light induced dielectrophoresis.72 Optimal methods for fluid manipulation, however, have advantages over traditional methods since the manipulation is contactless and light patterns used for fluid manipulation can be changed rapidly.

Optofluidics has great potential to bridge the dichotomy existing in the development of point-of-care diagnostic devices and to provide low-cost, autonomous sample processing capabilities for samples in relatively complex matrices. Optical manipulation techniques that can be used to control fluid motion or to transport molecules in fluids have recently been developed based on optical-to-hydrodynamic energy conversion,73 thermophoresis74 or thermoviscous expansion.75 Liu et al. used laser light to illuminate suspended photothermal nanoparticles near the liquid–air interface to generate liquid flows in microfluidic channels.71 A flow speed of 500 μm s^-1 was achieved when the illumination power was 20 mW. Weinert and Braun used a laser spot that moved along arbitrarily defined paths repetitively to remotely move fluids at a speed higher than 100 μm s^-1 on a two-dimensional plane without any valves, pumps, and fabricated micro-channels.76 The laser-induced temperature rise locally changed the viscosity of the fluid and resulted in a flow moving in the direction opposite to that of the laser movement. Besides generating flows in unstructured chambers, Weinert and Braun also utilized the same setup to transport microspheres across millimeter-long agarose gels and to mix biomolecules in gels.76

Besides fluid manipulation techniques, thermophoresis,74 which is the motion of molecules in a temperature gradient, has also drawn attention of the microfluidic and optofluidic community recently because of its ability to transport and manipulate molecules in solution. Thamdrup et al., for instance, used light induced local heating to demonstrate thermophoretic manipulation of DNA molecules in micro- and nanochannels.75 In addition, optical conveyors74 that can transport molecules in one direction in bulk water were created by combining thermophoresis with bidirectional flows generated by a moving laser spot based on thermoviscous expansion (Fig. 4).75 When multiple optical conveyors were arranged in a toroidal geometry to form an optical trap, single-stranded DNA molecules with lengths ranging between 5 and 50 bp were accumulated at the center of the trap within seconds.76 According to the simulation results, even when the temperature difference is only 5 K, the concentration of 50 bp DNA molecules in the center region is expected to increase 10-fold by the optical conveyors. Compared to conventional optical tweezers, which trap particles within ~1 μm of the focal point, the optical conveyor can trap and transport particles within an area of hundreds of micrometers. Since light completely drives the optical conveyor, the optical trap can be moved freely to collect molecules for long-term observations and for enhancing diffusion-limited surface reactions.

Since thermophoresis is very sensitive to the changes in the size, charge, and hydration shell of molecules, optical analytical methods based on thermophoresis have also enabled the measurements of the interactions between biomolecules and the separation of different biomolecules. Aptamer–target
interactions, protein–protein interactions, and low molecular weight binders were quantified in complex biological fluids such as human blood serum or cell lysate within seconds with a sample of less than 1 μl by measuring the time the molecules take to move away from a heated spot created by a focused laser beam. In addition, when a polyethylene glycol polymer solution forms a concentration gradient because of thermophoresis, mixtures of DNA and RNA, RNA of different lengths, or colloids of different sizes can be separated.

### 2.4. Optically induced flow reconfiguration and droplet manipulation

Reconfigurable optofluidic devices that have the ability to dynamically change flow pathways can be very useful for diagnostics in low-resource settings because of their advantages in cost and adaptability. With a reconfigurable flow network, the same device can process biological samples that require different sample preparation and analysis procedures. Further, in each diagnosis, the analysis performed downstream can be changed based on the results obtained in the previous step, which is useful when a series of analysis steps are needed to identify the biomolecules being tested. To move towards this paradigm, photoresponsive and thermoresponsive polymer gels that undergo a phase change under illumination have been utilized to create microfluidic valves and reconfigurable flow networks. Krishnan and Erickson, for instance, recently demonstrated the use of patterned light from a computer projector to create dynamic temperature patterns that locally trigger a reversible sol–gel conversion in a bio-compatible Pluronic polymer solution. A broadband absorbing substrate consisting of polydimethylsiloxane (PDMS) mixed with carbon black was used to increase the efficiency of photothermal conversion. Since the Pluronic solution changes from a low-viscosity fluid to a solid gel when heated to a critical temperature, by simply changing the light pattern, arbitrary solid regions were created, moved, and removed in a microfluidic network to dynamically reconfigure flow pathways and channel structures. Additionally, trapping of DNA molecules and nanoparticles have been demonstrated using this technique.

Optically induced Marangoni effects have also been used to drive microscale circulation to trap and transport single and multiple droplets. Thermal patterns used to induce the effects were generated using a computer projector and an absorbing layer. Since the induced force on droplets is dependent on the droplet size, it is possible to use this technique to select droplets of a particular size, which could be useful for sorting droplets in microfluidic chips.

2.5. Solar powered optofluidic devices

Usually, in optofluidic devices, infrared lasers are used for generating the thermal effects mentioned previously through optothermal conversion. However, if possible, replacing these lasers with solar light can make the devices simpler, lower cost, more portable, and ultimately more suitable for use in the developing world. To increase light collection efficiency, solar concentrators such as the one that consists of two-dimensional lens arrays and multimode waveguides, which homogenize and transport sunlight focused by the lens arrays, can be integrated with the optofluidic devices. In addition, in the case where optical waveguides are used to couple sunlight, it has been demonstrated that a cladding material that can change the refractive index locally in response to the moving sunlight can reduce the requirements on the mechanical tracking system used to maintain solar alignments. As a proof of concept, a colloidal suspension, the concentration of which is modulated by optically induced dielectrophoresis, was used as the cladding layer of the waveguide to achieve a reactive solar concentrator design.

3. Optofluidics for food safety, nutrition and agriculture

There is a significant need to provide enough safe and healthy food globally. In 2010, it was estimated that 925 million people suffer from chronic hunger. In addition, roughly 48 million cases of foodborne disease occurred in 2011 in the United States alone, and while it is hard to estimate, developing countries likely experience a much higher number of incidents.

---

**Fig. 4** A conveyor trap. (a) Biomolecules are efficiently accumulated by a combination of a temperature gradient and perpendicular bidirectional flow. Since thermophoresis predominantly locates the molecules at the colder top, the conveyor-like water flow transports the molecules to the center. Both the temperature gradient and the water flow are generated by a spot of enhanced temperature at the bottom, induced by the laser absorption in a thin metal layer. The water flow is the result of the coaxial thermoviscous pumping in the radial direction. (c) Short DNA is trapped from a diameter of 200 μm within 3 s. Longer DNA shows a stronger confinement. The single-stranded DNA oligos with lengths of 5, 10, and 50 bases are labeled with the fluorescent dye 6-carboxy-4',4',4',5,5,5'-hexachlorofluorescein, succinimidyl ester (HEX) to visualize the concentration. By reversal of the fluid flow, the molecules are transported off the conveyor, shown by 1000 base pair DNA stained with the intercalating dye TOTO-1. Scale bars are 100 μm. Reproduced with permission from ref. 78. Copyright 2009 American Chemical Society.
global population continues to grow, innovative technologies must be developed to meet the demand for providing safe, healthy, low-cost and low-environmental-impact food and agriculture.

Food quality is also becoming an important issue not only in the developing world, where many people are lacking essential nutrients in their diet such as vitamins, proteins or folic acid, but also in the developed world,92,93 where people are becoming increasingly health conscious and demanding when selecting foods.94

Optofluidics has the potential to innovate in several key areas including detection of food-borne pathogens for consumer safety, nutrition monitoring for consumer health, assessment of new food processing techniques and modified foods, effective health management of livestock, and optimized crop growth. Recently, several review papers have examined the application of microfluidics and nanotechnology to the food sector.95–99 Here, we briefly review some state-of-the-art devices and consider potential advantages that optofluidics could offer.

3.1. Food safety

Poor methods of food processing, especially in developing countries, may include undesirables such as bacteria or pesticides and may have high contamination rates, as demonstrated by continuing outbreak cases in the US alone recorded by the Center for Disease Control and Prevention.100 Safety assessment techniques must be developed to minimize the risk to the customer. For commercial use, devices must sensitively and rapidly detect various foodborne pathogens including bacteria, viruses and pesticides while maintaining a simple and inexpensive interface. In addition, advancements in nanotechnology have led to the use of nanostructures and nano-encapsulations to improve foods. Such additions must be thoroughly analyzed in the lab in order to understand their effects on human physiology before they can be safely implemented.101

3.1.1. Bacteria and virus detection. The ultimate aim in providing safe food is to reach a “zero tolerance” standard, in which no viable pathogens are allowed in particular foods.102 To realize this benchmark, detection sensitivity and analysis must be effective enough to identify trace amounts of pathogen in a small sample. Major targets of such techniques would be bacteria such as E. coli, Salmonella, Campylobacter, Listeria monocytogenes and Vibrio cholerae94 and viruses such as norovirus, rotavirus and hepatitis A and E virus.103 Conventional culture based methods, while reliable and accurate, require days to produce results of the pathogen detection. Therefore, many microscale biosensors have been developed recently to provide rapid detection of pathogens.104 As discussed previously, optofluidics is naturally suited for detection and analysis in very small volumes, and many techniques for disease diagnostics can be applied to food and drink safety.9 The ARROW device mentioned previously is promising for bacteria detection because of its ability to trap and detect a single E. coli bacterium with an optical power level of a few microwatts, which is about four orders of magnitude less than conventional optical force traps.38 The same groups are working to simplify the technology for low resource settings and recently demonstrated an ARROW design with an integrated on-chip spectral filter for multiple optofluidic detection uses (Fig. 5).39 As the authors point out, the filter technology developed could benefit other optical sensing methods that have also been used to detect foodborne bacteria such as Förster resonance energy transfer (FRET)105 and surface-enhanced Raman scattering (SERS).106

Direct detection of RNA viruses can be achieved using reverse transcription polymerase chain reaction (RT-PCR), and microfluidic detection of rotavirus was recently demonstrated by Li et al. using integrated heaters and sensors.107 The authors claim that their device would cost approximately $300, which while much less expensive than conventional PCR machines, is still too costly and complex for use in low-resource settings. As described above, the development of opto-thermal, or specifically solar-thermal techniques could introduce ways of performing such tasks much more cheaply and easily in the future.

3.1.2. Pesticide detection. Along with bacteria, high levels of pesticides also pose an environmental threat. Particularly, poorly regulated use of farm chemicals in developing countries often leads to accidental poisoning and death.108 Common methods for pesticide detection such as liquid chromatography and gas chromatography require high cost and slow sample preparation and measurement times, making them unsuitable to field use. To address this, several optofluidic methods have been developed, including ring resonators to detect organophosphorus pesticides109 and SERS for detecting methyl parathion.110 A recent review written by Llorent-Martínez et al. examines both electrochemical and optical pesticide detection schemes.111 The authors of that study indicated that a benefit of optical techniques is that they have often been shown to work with real samples, although miniaturization and multiplexing are key advancements that need to be developed to expand their utility to in situ conditions. As stated above, optofluidic designs have the potential to tackle both issues by allowing for complex fluid handling while minimizing the machinery required.
3.1.3. Analysis of nanotechnology-modified foods. The use of nanostructures and nano-encapsulated additives in food and inorganic nanomaterials in food packaging holds the potential to reduce transmittance of foodborne pathogens and may lead to less use of chemicals and improved properties such as storage time and nutrient uptake in new products. However, without extensive research to determine the ADME profile (adsorption, distribution, metabolism and elimination) and toxicological properties of new food additives, it would be unlikely for nanocarriers or inorganic nanomaterials to substantially benefit the food sector since their potential risk to the consumer cannot be assessed. In order to identify the biophysicochemical interactions, artificial cellular structures must incorporate nanomaterials to produce an environment that mimics the biological system. Optofluidics is well-suited for such conditions, as optical forces can be adapted to control and analyze both nanoscale particles and microscale cells while the microfluidics can simulate the necessary cellular micro environment. To shed light on the complex ADME process that the body takes with new food additives, optofluidic technology could help combine previous approaches to analyze the dynamics of integrated nanomaterial–microbiology systems.

3.2. Food nutritional analysis

In addition to food safety, food analysis is also concerned with quality analysis, which requires the determination of the chemical composition of foods. Fast and portable methods for food analysis are urgently needed in developing countries. Such methods could help aid workers and healthcare professionals identify deficiencies in essential nutrients that might affect a population. For example, in countries such as Sri Lanka and India, over 40% of women reportedly lack folic acid. This is a major problem, since the lack of folic acid in the diet of pregnant women is reported to cause neonatal neural tube defects and congenital abnormalities if the infant survives. Identifying the specific needs in each population using rapid and accurate food analysis is important in providing adequate food relief and addressing health problems.

In the developed world, because of increasing government regulations and international standards, the need for fast and accurate food analysis has increased. For example, in 2006 the Food and Drugs Administration (FDA) started requiring food companies to indicate trans-fat content on packaged food labels, one of the many new amendments to the Nutrition Labeling and Education Act (NLEA) of 1990. Moreover, because consumer choices are often driven by quality, food companies are relying heavily on analytical methods for food analysis in order to ensure a desirable final product. This is reflected by the initiative taken in 2011 by the Grocery Manufacturers of America to provide the content of a few select “nutrients to encourage” on the front of packages.

Food analysis is challenging because accurate measurements of specific nutrients are highly dependent on the food matrix or the nutrient composition of the food under investigation. Thus, different techniques might be required to analyze the same nutrients in different foods. Food analysis has undergone remarkable progress in the past century. The early wet chemistry methods have given way to instruments that use more sophisticated methods such as high-performance liquid chromatography (HPLC), near-infrared (NIR) spectroscopy, site-specific natural isotope fractionalization and mass spectrometry (MS). HPLC is a fast, highly sensitive and accurate method that can be used to quantify analytes such as sugar, phospholipids, vitamins and proteins. The high cost and complexity of HPLC instruments, however, make them impractical for many applications. A major problem in food analysis is that, since most instruments cannot handle food matrices directly, more than 80% of the analysis time is spent in sample preparation. Developments in the field of chemical sensors for food analysis have led to the so-called electronic tongues, which combine arrays of such sensors and a data processing system. In addition, optical methods are gaining momentum because of their advantages for quick and portable analysis. In the following sections, we identify several areas where optical biosensors have advantages over established methods.

3.2.1. Fast and low-cost optical biosensors for on-site analysis. Given that food companies must undergo food analysis at each step of their processes in order to ensure the desired final product, the development of smaller, faster and more portable instruments for food analysis could have a large impact on the cost of production. In addition, there is a need to develop field portable analytical instruments that can assess food quality and monitor ripening of fruit and vegetables. Although several groups are working on the miniaturization of HPLC and MS systems, it is unlikely that these methods will become portable and low-cost enough to be used for such applications.

Recent advances in photonics and microfluidics have made optical biosensors an interesting alternative to conventional analytical methods for portable, low-cost food testing. Label-free optical biosensors such as SPR and fiber optic biosensors are particularly promising because of their ability to detect multiple analytes with ultra-low volumes of sample. Advances in microfabrication and opto-electronic technologies have led to the development of low-cost multichannel SPR biosensors that employ a special diffraction grating structure to simultaneously excite surface plasmons and disperse the diffracted light for spectral readout. Multiple-channel SPR biosensors as shown

![Fig. 6](image-url) (a) A multichannel SPR biosensor device with the flow cell. (b) A scheme of the immunosensor format in the case of fluoroquinolones detection. Reproduced with permission from ref. 128. Copyright 2010 Elsevier B.V.)
in Fig. 6 have been used for simultaneous multi-analyte antibiotic detection in milk samples.\textsuperscript{128} Besides SPR-based biosensors, fiber-optical chemical and biological sensors could also be practically used for on-site analysis if they can incorporate families of chemically sensitive indicator dyes that can be interrogated using a single source.\textsuperscript{129} Advances towards low cost photo detector systems and low-loss plastic optical fibers could help commercialize optical biosensors.

3.2.2. Accurate and highly sensitive analysis of modified foods. In an era of increased awareness of health and nutritional needs, modified foods that are either adulterated or fortified with various nutrients have become increasingly common. Functional foods, meaning foods that may provide health benefits beyond basic nutrition, present new challenges since new methods must be developed not only for determining their concentration levels but also for determining their potential benefits for cancer prevention, anti-inflammation and antioxidant effects.\textsuperscript{130,131}

Optical biosensors can be used for fast, sensitive, and accurate assessment of biological compounds in functional foods, including vitamins, folic acid, various minerals, phytosterols, and phytochemicals.\textsuperscript{132} Phytochemicals are known for their antioxidant properties, and several optical biosensors have been developed to measure their concentration.\textsuperscript{132} Chaillou and Nazareno demonstrated the use of spectrophotometric methods for determining the antioxidant abilities of polyphenols.\textsuperscript{133}

In addition, optical methods have been used to determine the concentrations of amino acids in dietary supplements. Cruz et al. demonstrated a sensitive method for lysine detection in a syrup composed of several different amino acids.\textsuperscript{134} The method makes use of the cooperative binding between europium ions and lysine to enhance the resonance light scattering (RLS) of functionalized gold nanoparticles. Instrumental improvements in various techniques have pushed the state-of-the-art detection limit to the order of femtometers (10\textsuperscript{-15}), and this limit is likely to be pushed further in the coming decades.\textsuperscript{132} The impact of this is that we can now detect and study analytes that we could not before, and the number of analytes that need to be measured, studied and ultimately regulated will continue to expand.

Food adulteration is also becoming a significant problem, especially in developing countries, where food quality testing is not as common as in the developing world. This is a problem not only because it cheats the consumer but also because it can pose a serious health risk.\textsuperscript{135} Optofluidic methods have been shown to be particularly useful in fighting adulteration of typical foods such as extra-virgin oil, beer and milk.\textsuperscript{136} For example, detection of non-milk protein in milk powder using SPR has been demonstrated with a detection limit of 0.1\% of plant protein in total milk protein content.\textsuperscript{137} Techniques such as scatter colorimetry can be used to gather information on the color and turbidity content of liquids in order to classify extra virgin olive oils and beers. Ultraviolet, visible, and near-infrared absorption spectroscopy has also been used in the quality control process of olive oils and a variety of other food products.\textsuperscript{138,139}

3.2.3. Detection of vitamins and folic acid. Food analysis using optical methods presents good opportunities when the conventional methods are particularly complicated and time consuming, as is the case for folic acid and fat-soluble vitamins. Current methods of determining vitamin levels, especially fat-soluble ones, are complicated and vitamin-specific. Levels of water-soluble vitamins, such as thiamine (B\textsubscript{1}), can best be determined using HPLC, though it requires separation of analytes in order to avoid interferences.\textsuperscript{140} Fluorometric determination without phase separation of thiamine has been demonstrated as an alternative to HPLC.\textsuperscript{141}

Folic acid, a form of the water-soluble vitamin B\textsubscript{9}, is essential for numerous bodily functions and is especially important for women during pregnancy.\textsuperscript{142} Levels of folic acid and folate-binding protein (FBP), a protein that regulates the assimilation, distribution, and retention of folates in mammalian cells, have been measured in breakfast cereals, milk, and soy-based infant formulas using SPR.\textsuperscript{142–144} The methods make use of the specific interactions between folate-binding protein (FBP) and folic acid, which depend on folic acid concentrations in solution.

3.3. Individual health monitoring

With the increase in obesity and cardiovascular problems in the developed world, nutrition monitoring has become a major concern. In addition, studies have shown that nutritional status affects a patient’s response to illness and is even related to a reduced functional capacity of elderly people.\textsuperscript{145}

Despite the increase in public awareness, there have been few changes in the methods of nutritional assessments. Typically, a brief nutritional screening, including a physical examination, is used to identify patients in need of in-depth analysis. Despite their importance, nutritional assessments are not common among the general populations, and consequently, deficiencies in calories, proteins, essential fatty acids, vitamins, and minerals often go unnoticed.\textsuperscript{146}

There are few methods for in vivo nutritional monitoring since food analysis methods, such as the ones discussed in Section 3.2, are either too invasive for continuous monitoring or too difficult to miniaturize for on chip applications. However, a few methods, mainly optical, have been adapted for monitoring living tissues. The advantage of optical methods for in vivo applications lies in the fact they are potentially less invasive than mechanical or electrical methods for nutrient detection. Some groups have demonstrated the potential of optical methods for monitoring the evolution of nutrients on the skin, which is possible because infrared light can travel through tissues and interact with the various components of the skin.\textsuperscript{147} These interactions can alter the intensity, spectral composition and direction of the reflected light that can be collected and analyzed. The information that can be obtained using purely optical methods on the skin, however, is limited because primary nutrients are quickly broken down to their constituents during digestion prior to entering the bloodstream. Consequently, several groups have developed optofluidic methods for analyzing body fluids such as blood and sweat on chips.\textsuperscript{148} Methods for collecting body fluids including micro-needles\textsuperscript{149} and sweat-patches\textsuperscript{150} have been developed in parallel. The lab-on-a-chip approach is more versatile because it allows both optical and non-optical sensing methods to be integrated in a common device.

There is a real need for nutritional assessment devices that can evaluate nutritional deficiencies in patients more rapidly and regularly without relying heavily on physicians. In the following
sections we review the advances in in vivo optofluidic monitoring in the areas that will likely see rapid innovations in the coming years.

3.3.1. Continuous glucose monitoring for diabetes. Accurate carbohydrate detection, in particular glucose detection, has been a priority for several decades because of the prevalence of diabetes in the world.\textsuperscript{154} While this has led to the development of fingerpick tests, accurate and reliable continuous glucose monitoring devices are still not well established. Continuous monitoring of glucose is important because it could prevent issues associated with long periods of hyper- and hypoglycemia.\textsuperscript{152} Current FDA-approved needle-type amperometric enzyme electrodes that monitor glucose continuously such as the ones commercialized by Medtronic require frequent replacement of the enzyme needle.\textsuperscript{155} Thus, there is an opportunity for the development of minimally invasive optical sensors that can last much longer without the need for replacing parts.

Yuen et al. demonstrated that SERS can be used for monitoring glucose levels in vivo.\textsuperscript{156} In this case, a sensor chip was functionalized and implanted subcutaneously in a rat, and glucose concentrations in the interstitial fluid were monitored by measuring the surface-enhanced Raman spectra through the skin using spatially offset Raman spectroscopy (SORS). The authors suggested that the combination of SERS and SORS is a powerful technique that can be applied to in vivo sensing of other biological targets. Currently, the disadvantage of this approach is the high cost required for the optical components in such a device.

In vivo glucose detection has also been demonstrated using a functionalized hydrogel-optical fiber, where the detection is based on the glucose-induced contraction of the hydrogel.\textsuperscript{156} The hydrogel was fabricated on the end of an optical fiber, and the optical length was measured using an interferometric technique. Another promising method for in vivo glucose monitoring is single wall carbon nanotubes (SWNT) fluorescence because the photostability and near IR characteristics of SWNT fluorescence avoid in vivo transmission and sensor lifetime issues. Barone et al. have developed two SWNT-based sensors: an enzyme based sensor and an affinity based sensor.\textsuperscript{156} The Liepmann group at the University of California at Berkeley has developed an electrochemical device that allows for continuous monitoring of glucose.\textsuperscript{157} The device incorporates a micro-needle patch that draws interstitial fluid onto a chip with incorporated electrochemical sensors.

3.3.2. Identifying deficiencies in protein and essential fatty acids. The importance of a balanced diet containing adequate amounts of proteins and essential fatty acids is well known, however due to the lack of continuous nutritional monitoring methods deficiencies often go unnoticed.\textsuperscript{164} Studies have shown low levels or imbalance of essential fatty acids can lead to increases in blood viscosity, vasospasm, and vasoconstriction and can result in increased risk of several illnesses including osteoporosis.\textsuperscript{158,159} Protein deficiencies, common in both developing and developed countries, can cause a variety of health issues including mental retardation.\textsuperscript{160}

Several groups have developed methods for in vivo monitoring of essential amino acids. Most methods make use of microdialysis and capillary electrophoresis (CE) techniques.\textsuperscript{161,162} Microdialysis is a popular method because it allows for good temporal resolution. It has been used to investigate neurotransmitters in the brain extracellular fluid and drug delivery.\textsuperscript{163} Following microdialysis, the sample is investigated using either liquid chromatography (LC) or CE, which has been shown to require a smaller sample volume and therefore offer better temporal resolution than LC. Zhou et al. was one of the first to develop a separation based biosensor capable of near real-time analysis of aspartate and glutamate.\textsuperscript{164} Following microdialysis sampling, the primary amine analytes were derivatized before traveling to a microinjection valve and reaching the CE column. Using this system, sample amino acids from brain dialysate were analyzed with a temporal resolution of less than 2 minutes and a detection limit of 0.1 µM. More recently, microchip devices for amino acid monitoring with improved temporal resolution, miniaturization, and fluid handling capabilities have been demonstrated.\textsuperscript{164,165} Dialysis based techniques in conjunction with CE are useful in the detection of analytes that cannot be detected using conventional biosensors.

Measuring fatty-acid levels in tissue usually involves time consuming processes for extraction and analysis such as gas chromatography.\textsuperscript{166} Yoshida et al. developed a direct method for measuring dietary fatty acids on human lips using Fourier transform infrared spectroscopy (FTIR) with attenuated total reflection (ATR).\textsuperscript{167} The lips were chosen since they are unaffected by sebaceous activity that could mask changes in lipid composition following ingestion of fatty acids. The transport of docosahexaenoic acid (DHA) from blood vessels to the lips is very rapid and can be detected less than 2 hours after the intake of foods containing DHA. It is noted that, because the lip surface in humans is unique, with less barrier functions than normal skin and blood vessels in the dermis, the transport of biomaterials from blood vessels to the lip surface is more rapid than to other skin surfaces, thus being ideal for the optical detection of a variety of nutrients.

3.3.3. Salts, minerals and vitamin monitoring. Measuring ion concentrations directly in bodily fluids such as sweat can be correlated to electrolyte concentrations in plasma. The Diamond group at Dublin City University has developed a textile based patch with integrated optical detection system for sweat monitoring (Fig. 7).\textsuperscript{168} The device consists of a fluid handling system that collects the sweat inside a narrow channel that flows over an area with an immobilized pH sensitive dye. A paired emitter-detector dual LED is used to provide continuous quantitative measurements of pH. This approach has several potential
applications, including measuring sweat rate during exercise.\textsuperscript{169} In addition, the sweat contains other biomarkers that can be used to estimate nutrients levels in the interstitial fluid.

Sweat monitoring has already found commercial applications for drug\textsuperscript{170} and cystic fibrosis testing.\textsuperscript{171} Developing microfluidic devices for continuous monitoring of potassium, sodium, and chloride ion concentration could be the next step.

Vitamins are essential compounds that cannot be synthesized in high enough quantity by the body and need to be obtained through diet. Kokaiová and Matějka recently demonstrated the application of Fourier transform SERS spectroscopy for the detection of B-group vitamins riboflavin, nicotinic acid, pyridoxine, and folic acid on both gold and silver surfaces.\textsuperscript{172} In addition, there are few methods for simultaneous determination of several kinds of fat-soluble vitamins in biological fluids. However, these methods, such as HPLC analysis using diode array detection, usually involve time consuming steps that are not suitable for \textit{in vivo} applications.\textsuperscript{173} Mata-Granados \textit{et al.} proposed a fully automated method for determining fat soluble vitamins and vitamin D metabolites in serum.\textsuperscript{174} After a multistep separation process, ultraviolet detection was performed at several wavelengths for each target.

### 3.4. Managing animal and plant health

Solving food-related problems requires addressing the source. Most foods originate on the farm, and therefore it is essential that new technologies can effectively manage the health of livestock and crops. Improving livestock health can lead to safer and more effective production of meats, diminishing the need to further process or test foods for health purposes. This may also reduce costs for farmers through less use of medicine and animal health checkups. In addition, enhancing crop health can heavily affect both the food and energy sectors.

Corn, for instance, is used for food products such as sweeteners, starch and corn oil in addition to basic feed. Furthermore, the demand for renewable fuels has led to over a quarter of all corn reaped to be used to produce ethanol in 2009.\textsuperscript{175} Microfluidics and nanotechnology have been recognized as transforming technologies in veterinary therapeutics through their applications in diagnostics, drug delivery and fertilization.\textsuperscript{176,177} and are beginning to find applications in plant science.\textsuperscript{178,179} For example, García-Cordero \textit{et al.} recently developed a portable “point-of-cow” reader system based on sedimentation cytometry to diagnose bovine mastitis, a common and highly costly mammary gland infection.\textsuperscript{180} As several diagnostic technologies are discussed in previous sections, here we will only examine applications in the areas of fertilization and animal and plant drug delivery.

#### 3.4.1. \textit{In vitro} fertilization

Over the past five decades, infertility in cattle has dramatically increased. Even with artificial insemination methods, the first-service-pregnancy-rate, a measure of pregnancy success, has dropped from 70\% to 40\% in the United States, which is well correlated with the increased milk production demand that leads to an imbalance of cattle physiology.\textsuperscript{181} Along with measures to prevent disease, researchers must develop improved breeding methods such as \textit{in vitro} fertilization (IVF), which must reliably select healthy oocytes and sperm. The selection process is traditionally done subjectively \textit{via} visual analysis, and therefore there is increased interest in the microfluidics community to create devices that automate the selection process.\textsuperscript{178,182} Optofluidics presents a noninvasive and simple approach to studying the spectral properties of oocytes\textsuperscript{183} and the swimming force of sperm.\textsuperscript{184} For example, Vidberg \textit{et al.} demonstrated monitoring the stage of oocyte development and fertilization by measuring the change in its transmission spectrum, providing for a more definitive selection process.\textsuperscript{185} Some works have begun integrating various components of the IVF process\textsuperscript{186,187} though a completely automated system has not yet been demonstrated. In the coming years, devices must combine on-chip oocyte selection, sperm selection and culturing techniques to develop fully integrated IVF devices.

#### 3.4.2. Localized drug delivery

Typically, animals receive antibiotics, probiotics and other therapeutics \textit{via} feed or injections. Because these are not targeted approaches, medicine must be delivered as a preventive measure or after symptoms appear and often in bulk to reach the affected area, leading to unnecessary risk to the animal and additional cost to the owner. The development of “smart” delivery techniques can potentially reduce these burdens by being able to target localized regions and to be controllably activated.\textsuperscript{176,177} In particular, gold nanostructures, owing to their surface bioconjugation and optical properties, have made a tremendous impact in nanomedicine research and in particular cancer treatment\textsuperscript{188,189} and triggered release of bio-agents.\textsuperscript{190} Among the wide range of potential stimuli for manipulation of gold nanoparticles (\textit{i.e.}, mechanical, heat, pH, magnetic and electric fields, light and acoustic), optical activation offers arguably the best combination of properties for \textit{in vivo} studies by incorporating high absorption, fast reaction speed, photostability and tenability, and noninvasiveness.\textsuperscript{191,192} For example, Yavuz \textit{et al.} developed porous nanocages coated with the copolymer pNIPAAm-co-pAAm, a combination of poly(N-isopropylacrylamide) (pNIPAAm) and acrylamide (AAm).\textsuperscript{193} This copolymer is thermosensitive and exhibits a phase change from hydrophilic to hydrophobic when its temperature is raised above its lower critical solution temperature (LCST).\textsuperscript{194} Through heating using a near-infrared laser, the local rise in temperature forces the collapse of the polymer chains, thus releasing the contents of the nanocage (Fig. 8). Due to the high transparency of soft tissue in the near-infrared region, this technique could be used to heat the gold nanoparticles \textit{in vivo}.

Similar to nanomaterial food additives, many technologies in this field are still proof-of-concept demonstrations that require further ADME studies to determine behaviors such as the condition of the nanoparticles after therapy, biocompatibility, and reactions to various physiologies. Optofluidic environments allow the researcher to control both the biological environment and the optical input, providing preferable conditions for these kinds of studies.

#### 3.4.3. Improving crop health

Currently crop harvest is low, as biotic stresses caused by insects, diseases and weeds cause over a 40 percent loss in yield, even with the use of pesticides.\textsuperscript{195} Part of the reason for this is that pesticides are typically applied through general spraying, with only a small fraction of chemicals
reaching the target. These limitations have led to interest in developing micro- and nanotechnologies that can controllably deliver pesticides and fertilizers and the study of toxicity effects of nanoparticles on plant health. Akin to drug delivery, regulating the distribution of pesticides and fertilizers optically is appealing due to its non-invasiveness and high localization. Analogous to nano-drug delivery in animals, nanoparticles designed for plants should be spatially and temporally controllable and reliably triggered and regulated at targeted sites. In addition, nanoparticles must be able to pass through the stronger barrier presented by the cell wall around plant cells. A few works have recently incorporated external stimuli to manipulate nanoparticles for application in plants. For example, González-Melendi et al. demonstrated concentration of magnetic nanoparticles inside pumpkin plants near the location of magnets. Also, Torney et al. used dithiothreitol as a chemical trigger to release molecules from gold-capped mesoporous silica nanoparticles (MSN) (Fig. 9). The use of optical stimuli could provide the same advantages of high localization and non-invasiveness as seen in animal drug delivery techniques to plants. To apply light stimuli here, nanoparticles must be designed such that their absorption peak does not overlap with wavelengths that plants absorb for photosynthesis, typically around the ultraviolet and infrared regions. Optofluidics can be utilized to produce the complex interactions between light stimuli, nanoparticles and plant cells and study how optical forces may affect nanoparticle invasion dynamics and therapeutics inside a plant cell matrix.

4. Optofluidics for water purification and desalination

Lack of clean, fresh water is projected by the National Academy of Engineering to be one of humanity’s Grand Challenges in the coming years, as current fresh water supplies dwindle rapidly in the face of household consumption, irrigation and industrial use. Even now, around 1.2 billion people are estimated to be without access to safe drinking water, with significantly more lacking basic sanitation, leading to millions of deaths from diarrhea related deaths caused by unsafe water. It is essential that we look outside the traditional fresh water sources to complement our water supply. Desalination, the process of converting salty seawater and brackish water into fresh water, is an attractive alternative since 97% of the water present on earth is in the form of seawater and can therefore be an almost unlimited supply of potable water. Also, seawater desalination is a practical solution as nearly 70% of the population lives within a 70 km strip bordering the seas, thus easing the distribution concerns.

4.1. Desalination

There are numerous desalination technologies existing currently with the installed desalination facilities producing over 19 billion m$^3$ of fresh water per year. A recent review by Phillip and Eli-melech on desalination technologies discussed the outlook of existing technologies with respect to energy required and its effect on the environment. As detailed there, reverse osmosis (RO) is currently the leading desalination technology and is capable of producing water at costs comparable to traditional water sources. The energy required for operation of plants is, however, usually in the form of high-grade electricity. Moreover, the high efficiency plants are necessarily large scale leading to massive capital and maintenance costs. Other desalination technologies, mainly based on thermal desalination, including...
multistage flash distillation and membrane distillation, are either dependent on non-renewable fuel sources, therefore cost effective only in energy rich countries, or through use of renewable sources, which increases production costs significantly. A few recent reviews have covered the use of renewable energy sources and technologies for desalination purposes.

For poor and developing countries or communities that cannot afford the high capital costs or lack cheap access to high-grade electricity or other fuel sources, it may be more economical to develop smaller scale technologies that can be implemented as personal household units or for small communities. An excellent method for such an application was recently developed using ion concentration polarization. It however required high-grade electricity for its operation, limiting its use to places where such a resource is readily available. Although solar energy can be converted to electricity, a more practical and efficient alternative is to utilize photothermal conversion for distillation cycles in a compact fluidic cell. One such device, based on direct solar thermal heating, was demonstrated by Ho and Chen using a direct contact membrane distillation process on a small-scale chip (Fig. 10(a)).

Microfluidics is an especially attractive option for direct solar thermal heating since along with offering high surface to volume ratios for more uniform and efficient heating, it also offers the possibility of creating tight thermal gradients that can be useful for generating highly efficient distillation cycles. Additionally, a number of techniques including direct heating through a focused laser, using a broadband absorber such as PDMS mixed with carbon black, surface plasmon heating through gold nanoparticles or use of infrared absorbing dyes have been demonstrated, which are capable of converting incident light to directly heat the enclosed fluids. Since addition of a membrane not only lowers the distillation rate but also increases maintenance costs due to membrane replacements, an ideal alternative would remove the need for such a membrane. In this respect, we see the distillation of photothermally heated water through a trapped air bubble in a microfluidic system as an important first step in realizing a solar driven microfluidic desalination system. A possible drawback of using microfluidic technology for desalination is the prospect of low output volumes. With improved fabrication technologies, however, and availability of cheap polymers such as PDMS for microfluidic fabrication, the technology can potentially be scaled up for personal use or for small-scale plants.

4.2. Water sanitation

Poor water sanitation is another major roadblock in providing clean and safe water for human and livestock consumption. Waterborne bacteria and viruses are responsible for intestinal infections and diarrheal diseases, leading to poor digestion and subsequent malnutrition. In addition, a large number of chemical contaminants, varying from heavy metals to pesticides to complex compounds, can both contaminate the groundwater sources and enter the water supply due to wider industrial and agricultural usage. This can be of a much more serious concern in developing countries where necessary regulations are either lacking or weakly implemented, leading to widespread dumping of chemicals in water supplies meant for human consumption. Detecting contaminants and waterborne pathogens early and quickly can be an important first step to prevent widespread infection and disease from contaminated water sources. A significant amount of research has therefore been conducted over the past years to develop devices that can detect the wide variety of contaminants present in water.

4.2.1. Detection of waterborne contaminants. Detection for waterborne pathogens is typically carried out by using specific antibodies, aptamers or other biomolecules such as carbohydrates and antimicrobial peptides. As detailed in the sections above, application of optical and plasmonic methods in the field of biosensing is a popular and well-developed field of research. Since water could be contaminated with numerous contaminants, all existing in very small quantities and dilution, optical sensors are well-suited for this purpose due to their unique benefits – high sensitivity, label free and highly multiplexable nature – over other types of biosensors. Various optical and plasmonic biosensors have therefore, been developed specifically for water pollution detection and have been covered by recent review articles.
Multiple fluorescence based detectors have also been developed for water monitoring, offering the advantage of being both easy to use and relatively quick. Particular note should be taken of the RIANA device and the AWACSS devices, which were developed for detection of organic contaminants, and have also been field tested in Europe. They are both based on total internal reflection fluorescence (TIRF), with the AWACSS device offering more integrated technology, including microfluidics and optical detection and further multiplexing than the RIANA device. A portable and integrated optofluidic device based on algal fluorescence was also recently reported (Fig. 11). Algae are known to be extremely sensitive to external contaminants, which even in small quantities are able to inhibit its photosynthetic activity. Using integrated organic light emitting diodes (OLEDs) and photo detectors (OPDs) on a microfluidic chip, the fluorescent signal emitting from the algae solution, used as an indicator for photosynthetic activity, was measured. Another recent example of a low cost, disposable microfluidic chip came in the form of an immuno-NASBA (nucleic acid sequence-based amplification) chip which was used to detect waterborne pathogens. The device was designed for parallel, multiplex operation and depended on detection of pathogen RNA by amplification of the RNA within the solution, thus allowing for highly sensitive detection. Final detection was then carried out by fluorescent measurement that could be read by a standard microplate reader.

In addition to food- and waterborne pathogens such as bacteria and viruses discussed above, heavy metals are another form of contamination often found in water supplies. They can enter the environment and water systems both through natural processes such as volcanic emissions and human activity such as smelting. Such outbreaks can be devastating, as demonstrated by the arsenic contamination of water in Bangladesh and West Bengal, which still affects millions of people. A few microfluidic techniques have been developed for detecting heavy metals, including bacterial-based assays for monitoring arsenic and mercury detection schemes using gold nanoparticles. The bacterial-based bioassay developed by Buffi et al. exhibits several characteristics fitting for low-resource use including a low limit of detection, storage capability, and simplicity of operation, although it requires a microscope for detection. It may be possible for this technique to integrate optofluidic detection techniques such as optofluidic lensing previously used to develop a complete portable system. On the other hand, He et al. designed gold nanoparticles that bind to mercury ions, which lead to a color change observable by the naked eye in the presence of 5 μM mercury, thus removing the need for microscopes or lensing for detection. Placed in a simple microfluidic device, this allowed for cheap and power-free detection of mercury spiked into river water. Similar gold nanoparticle schemes have also been demonstrated for detection of lead, copper and silver ions. In these examples, a major concern is their reliability with real water samples that contain a number of additional contaminants. It is possible for the optofluidic sample handling techniques traditionally used for biological samples to be modified to process contaminants present in water.

4.2.2. Optofluidics for water treatment. Despite the recent development and demonstration of the above mentioned low cost microfluidic devices, there is still a need for devices in developing countries which could be operated without sophisticated lab equipment and highly trained lab technicians or professionals. Therefore, it is important to also look at effective water treatment methods that can be employed even when water monitoring is not feasible.

Water treatment methods need to account for both disinfection – elimination of waterborne pathogens – and decontamination – removal of organic and inorganic chemical contaminants. Currently employed water treatment methods mostly use chemicals such as chlorine, which can lead to formation of more complex compounds that can be hard to remove from nature. In addition, such treatments have been shown to be ineffective in removing certain pathogens. Moreover, these methods might not be readily available or applicable in many developing regions due to lack of proper
infrastructure. Therefore, there is an urgent need for the development of effective low cost disinfection and decontamination methods that can ideally be employed at point-of-use, removing the dependency on large water treatment plants and massively organized water distribution systems.

UV radiation has long been known to be harmful to microbes and can therefore rid the water of large number of pathogens. Solar disinfection has therefore been identified as a cheap and effective method of disinfecting water.\textsuperscript{196,231} An organization SODIS (Solar Water Disinfection),\textsuperscript{232} which promotes solar water disinfection in developing and third world countries, has been established and has been endorsed by international organizations such as the United Nations Children’s Fund (UNICEF), Red Cross and WHO. However, even though solar irradiation is widely available, only a small fraction of it falls under the 320–400 nm range, which is the most harmful for microbes. Additionally, it has been shown that the solar disinfection is largely ineffective in the 12–40 °C range, and the temperature needs to be raised to 50 °C for significant improvement in bactericidal rates.\textsuperscript{234} Again, as discussed with respect to desalination, optofluidics has the potential to effectively address these particular considerations. The large surface area to volume ratio achievable in microfluidic devices can ensure that the UV irradiation available is efficiently deployed over the water, while the various solar heating techniques discussed above – plasmonic, infrared absorbing dyes – can ensure that the temperature of the water is raised to maximize the bactericidal rates.

Besides direct solar disinfection, a number of photocatalytic techniques for water treatment have also been developed. As shown in Fig. 12(a), photocatalytic treatment depends on the generation of a highly reactive species in the solution through photo excitation of a catalyst layer (typically TiO$_2$). The reactive species generated can then reduce organic contaminants to harmless products or disinfect water. This technique has been widely researched due to its various applications and has been subject of review papers recently.\textsuperscript{233,234} Small scale prototypes for solar photocatalytic water treatment, SOLWATER and AQUACAT projects,\textsuperscript{203} have also been developed for deployment in rural countries. Optofluidics can again serve as an addition to the current photocatalytic technology due to the efficient transport phenomenon exhibited in microchannels. A microchannel would allow for faster diffusion rates to the catalytic surface due to smaller diffusion distances, while the laminar microflow in the channel can efficiently remove the products from the catalytic reaction, thus preventing back reactions and increasing the rates of the favorable forward reactions. An integrated optofluidic chip for photocatalytic water treatment that demonstrates these benefits was recently developed (Fig. 12(c)).\textsuperscript{235} In that work, researchers demonstrated much higher reaction efficiencies and significantly larger rate constants than a bulk container.

5. Optofluidics for energy applications

It is estimated that around 1.6 billion people currently lack access to electricity, with a majority of these residing in developing countries,\textsuperscript{236} which leads to a poor quality of life. Further, the majority of the existing electricity generation in developing countries is through non-renewable sources like coal and oil\textsuperscript{236}... resources which are becoming increasingly scarce and subsequently expensive. Moreover, additional use of these resources could significantly worsen global warming due to increased carbon emissions. In such a scenario, it is in the interest of these countries to develop renewable energy sources that can be either converted to electricity or used for heating and lighting purposes directly. Solar power, being the most abundant and widely available resource,\textsuperscript{237} is an obvious choice to explore and develop.

Even though solar photovoltaic cell technology has been developed significantly over the years, the costs associated with it are still large,\textsuperscript{236} with infrastructural and maintenance costs making it infeasible for large-scale adoption in developing countries. In such a scenario, it is advisable to develop ‘off-grid’ resources that can be employed locally and therefore avoid high infrastructural costs.

One of the more attractive alternatives is the development of photocatalytic fuel production — a process in which photo activated catalysts are used to drive chemical reactions for fuel production. One of the more popular examples is the splitting of water molecules to produce oxygen and hydrogen, which can be stored and used as a fuel. This technology has been dubbed as “artificial photosynthesis” due to the similarities with the natural photosynthesis process exhibited by plants. In a similar vein, Nocera and colleagues have recently reported the development of an ‘artificial leaf’\textsuperscript{238} — a silicon cell coated with catalysts, which when placed in water and exposed to sunlight starts producing hydrogen without the need of any external wires or instrumentation. Another group has demonstrated an artificial photosynthesis process on a microfluidic chip making use of the efficient transport characteristics offered by microfluidics to enhance the efficiency of the fuel production.
process.\textsuperscript{299} Recently, Hoang \textit{et al.} demonstrated a photocatalyst that can operate in the visible spectrum, which can lead to a significant improvement in the efficiency of these devices under ambient sunlight.\textsuperscript{299} We refer the readers to a recent review by Erickson \textit{et al.} for a detailed discussion on the state of the art photocatalytic technology and its various optofluidic prospects.\textsuperscript{190}

Photobioreactors, which are devices that use photosynthetic microorganisms such as algae or cyanobacteria for producing higher energy fuels using sunlight and carbon dioxide, represent another important source for production of biofuels. Biomass fuels are an important source of household energy in developing countries and especially in many African countries where they are estimated to provide energy to nearly 90 percent of the households.\textsuperscript{244} However, currently most of the fuel needs are met by burning wood or charcoal, neither of which is good for the environment, and which are in increasing danger of being depleted.\textsuperscript{241} Further, these fuels are highly inefficient and produce pollutants that have been linked to a large number of deaths.\textsuperscript{248} Other options include using crops such as corn or soybean for the production of biodiesel. However, this would put them in direct competition with food crops for the limited arable land and fresh water sources available for agriculture,\textsuperscript{242} which are already insufficient for feeding the growing populations in developing countries. Photobioreactors, on the other hand, can be developed in non-arable land and algae and bacteria can be grown using seawater or even wastewater.\textsuperscript{243,244} Further, a number of algae and bacteria have been identified and genetically optimized for the production of fuels.\textsuperscript{245} One of the main technological challenges is the design of photobioreactors so that they can be optimized for both sunlight capture and distribution, and developing efficient fluidics for efficient nutrient and fuel transport leading to maximum production of biomass and fuel per unit area. For example, Ooms \textit{et al.} recently demonstrated use of evanescent light from TIFR for production of fuel from a cyanobacteria.\textsuperscript{246} We refer the readers to recent reviews on photobioreactors design\textsuperscript{11,246,247} for a detailed discussion on these aspects.

6. Summary

In this article we have reviewed optofluidic techniques developed recently and discussed the possibilities of extending them to address some of the most important challenges in both the developing and developed world. We have attempted to show that, with the ability to simultaneously and precisely control fluids and light, optofluidic devices have the potential to mitigate problems in a number of areas and are not limited to diagnostic applications. While the discussions mainly focus on the applications in low-resource settings, we emphasize that the developed world can also benefit from optofluidic technologies. We have explored the possible research directions for optofluidics and indicated the potentially significant impact that relevant research could bring to the world.

Acknowledgements

M.M. acknowledges support from the National Science Foundation Graduate Research Fellowship under Grant No. DGE-0707428. V.O. acknowledges support from the National Science and Engineering Research Council of Canada (NSERC) through a Postgraduate Scholarship. D.E. Acknowledges support from the US National Science Foundation CBET division, through grant 0846489.

Notes and references

1 World Population Prospects: The 2010 Revision, Highlights and Advance Tables, United Nations, Department of Economic and Social Affairs, Population Division, 2011.
2 Millennium Development Goals Reports, United Nations Department of Economic and Social Affairs, 2011.
18 H. A. Atwater and A. Polman, Nat. Mater., 2010, 9, 205–213.
30 C. A. Barrios, Sensors, 2009, 9, 4751–4765.
31 S. Mandal, J. M. Goddard and D. Erickson, Lab Chip, 2009, 9, 2924–2932.