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CONVERGENCE – BIG POTENTIAL: MICROFLUIDICS FOR FOOD, AGRICULTURE AND BIOSYSTEMS INDUSTRIES

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ABSTRACT Microfluidics, a rapidly emerging enabling technology has the potential to revolutionize food, agriculture and biosystems industries. The principles of eletrokinetics, electro-hydrodynamics, and thermo-capillarity of microfluidic devices help solve important scientific problems that are difficult using conventional technologies. Microfluidic devices allow real-time temporal and spatial sensing in food safety. Nano particle encapsulation of fish oil by spray drying through efficient emulsification; detection of the presence of residues, trace chemicals, antibiotics, pathogens and toxins in the food and water supply monitoring; in micro and nano-filtration to improve food quality; analysis of antibiotics in dairy food products by chip based diagnostic system are few examples of potential applications of microfluidics in food industry. Microfluidics also has the potential to generate novel food structures by changing the way the food processing will be done through emulsions and foams, fluid mixings and dispersions. Monitoring nutrients and sorting plant cells to increase crop quality and production; effective delivery of biopesticides by agricultural spray equipments are emerging applications of microfluidics in agriculture. Applications of microfluidics in the animal science sector include simplifying traditional in-vitro fertilisation procedures in animal breeding, animal health monitoring, therapeutic intervention, and nucleic acid delivery systems using DNA molecules for animal vaccines and animal control agents. The objective of this review is to synthesize information on microfluidic systems and devices that features integrated operations with simple reliable components with applications in agriculture, food and bioprocessing industries.

Keywords: Microfluidics, Food, Agriculture, Nano-emulsion, Foams, Micro-structure.

INTRODUCTION With rapidly growing global population resulting in an ever-increasing demand for food and new energy resources, there is a significant demand for food, agriculture and biosystems research to deliver food, drink, and biomaterials with low cost, low environmental impact systems. Agricultural and Biosystems researchers around the world are focusing on every aspect of food chain from the farm to the fork by adopting state-of-the-art technologies to turn raw materials into food and biomaterials. To answer the complex set of engineering and scientific challenges in the agri-food industry,

innovation is needed for new processes, products and tools. Microfluidics is one of the top 10 emerging technologies that will change the world market by having a profound impact on the economy and how we live and work (Technology Review 2001). Microfluidic systems (often indicated as Micro Total Analysis Systems (μTAS) or Lab-on-a-chip (LOC) systems) offer promising potential for the food, agricultural and biosystems industries.

Microfluidics is generally defined as the science and technology of systems that process or manipulate small (10^{-9} to 10^{-18}) litres of fluids, using channels with dimensions of a few to hundreds of micrometers (WhiteSides 2006). The field of microfluidics technology is inherently interdisciplinary and covers a whole spectrum of science including physics, chemistry, engineering, microtechnology and biotechnology. The principles of eletrokinetics, electro-hydrodynamics, and thermo-capillarity with small dimension parameters in space and time for microfluidic systems help to solve important scientific problems that are difficult using conventional technologies. The characteristics of microfluidic technology such as laminar flow, large surface-to-volume ratios, and surface tension and capillary effects at the micrometer scale are important and make the devices efficient for processing and analyzing complex samples. The distinct advantages of microfluidic technology compared to the conventional fluidic systems are low fabrication cost, enhancement of analytical performance, low power budget, low consumption of chemicals and better biocompatibility. The benefits associated with miniaturization are fast analysis, short reaction times, low sample and reagent volumes, reduction of the size of equipment, possibility of portable devices and parallel operation for multiple analyses.

The overall market for microfluidics products is experiencing an annual growth rate of 15.5% (BCC Research 2004) and forecasted to exceed US$ 3 billion in market revenues in 2014 (Frost and Sullivan 2009). There are about 269 companies in 31 countries, 35 contract research organizations, and 118 university research groups worldwide, that are actively involved in developing methodologies, processes, tools and devices for microfluidics systems (Yole 2009).

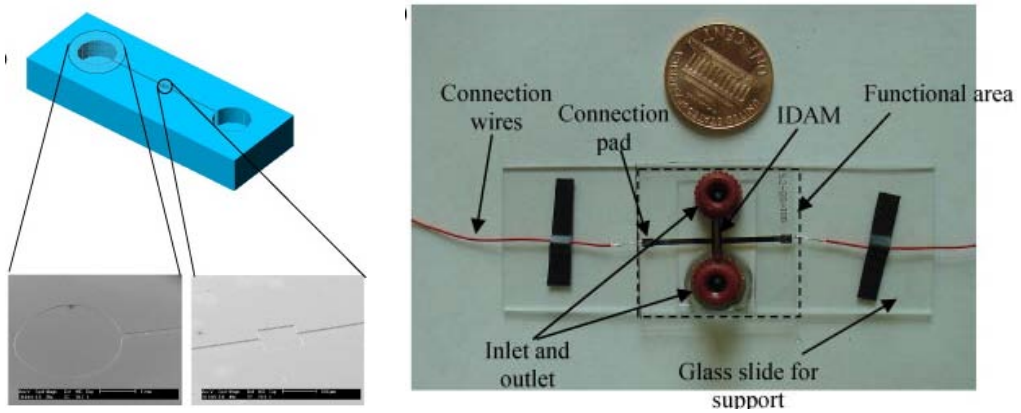
Applications of microfluidics to the food, agriculture and biosystems sector are relatively recent. Microfluidics being a critical enabling technology provides unique solutions by linking the micro components of the device with the macro-environment. Microfluidic technology provides unprecedented capabilities in bringing scientific solutions, methods and tools to realize the potential of agricultural products for quality and safety. In spite of the availability of only a few commercial microfluidic systems in pharmaceuticals and life sciences sector through academic and industrial research, the field of microfluidics has a strong competitive advantage in the agri-food, and biosystems market over other microfluidic applications.

In this review, we intend to summarize the existing applications of microfluidic systems that are relevant to food, agriculture, nutraceuticals and biosystems industries and to identify outstanding challenges. The scope of this review is to cover the existing microfluidics-based technology as applied in the 1) food safety and security, 2) food and biomass processing, 3) animal science and 4) plant production systems. The scope of this study also reviews future perspectives of microfluidic technologies and the related sub-technologies in light of the emerging needs of the agri-food market. The brand and the

company names mentioned in the manuscript here are for the purpose of information only and not intended as an act of promotion or endorsement.

Food safety The most common food-borne pathogens are *Campylobacter Jejuni*, *Escherichia coli* (*E. Coli*) O157:H7, Shigella, *Listeria* and *Salmonella*. The worldwide economic impact of food-borne toxins producing illnesses and outbreaks are substantial and significant. *E. coli* O157:H7 and *Salmonella* pathogens alone have caused approximately 1.47 million food borne illnesses and 453 deaths in the United States in 2008, with an estimated $3.12 billion in associated medical costs, productivity losses, and costs of premature deaths (USDA 2010). Traditional methods for the detection of food borne pathogen rely on culturing of the bacteria onto agar plates which are time consuming. Microfluidic devices allow cheap, efficient, real-time temporal and spatial detection of the presence of residues, trace chemicals, antibiotics, pathogens and toxins in the food and water supply monitoring. With the lab-on-chip approach, it is possible to quantify and detect the infection rapidly within few minutes from food and thereby the quality monitoring can be done comprehensively from the farm to the fork encompassing all aspects of food production through transportation and food processing to retail and food service.

The detection and estimation of pathogen concentration in the food and water samples is generally achieved by quantification of whole pathogen cells, metabolites release or pathogen specific protein/nucleic acid sequences. Varshney et al. (2007) have developed a microfluidic flow cell (Figure 1) with embedded gold interdigitated array of microelectrodes (IDAM) integrated with magnetic nanoparticle-antibody conjugates to detect pathogenic bacteria in beef samples. This is a novel label-free impedance biosensor for the direct impedance measurement of bacterial cells without using redox probe or antibodies on the surface of electrodes. This microfluidic biosensor was able to detect as low as 1.2×10^3 cells of *E. coli* O157:H7 in beef samples, in just 35 min.

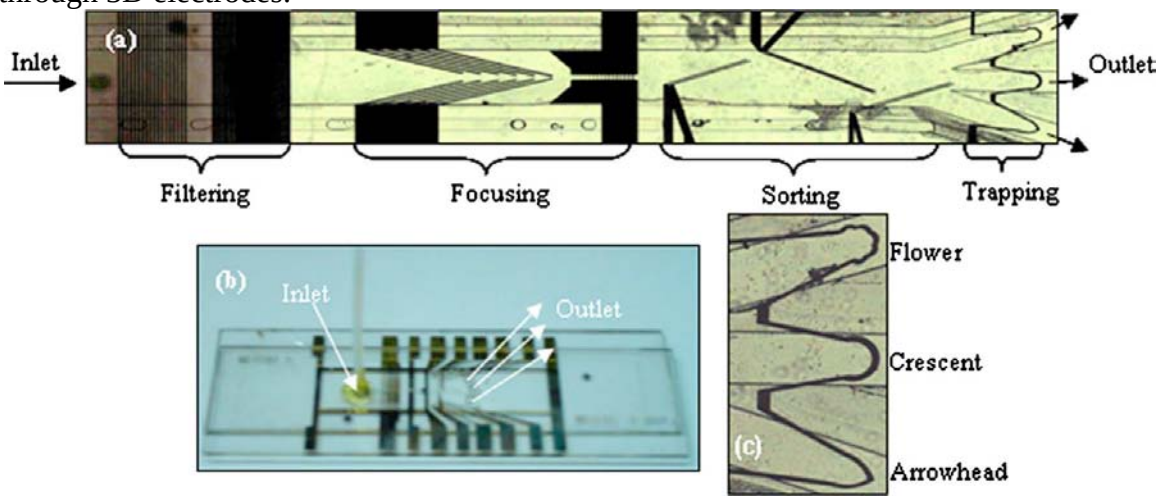


Microfluidic device for bacteria detection in beef samples

Figure 1. (A) A microchannel with a detection microchamber, and inlet and outlet channels, (B) An assembled microfluidic flowcell with embedded interdigitated array microelectrode and connected wires. Reproduced with permission from Varshney et al. (2007).

Microfluidic devices, can possibly isolate pathogen from suspended particle concentration mixture during dielectrophoresis by regulating the flow transport. In a microfluidic device developed by Gagnon and Chang (2005), while all suspended particles are swept towards the outlet along the fluid flow, target pathogens were directed towards the stagnation points by applying electric field. They were able to achieve this phenomenon by converging fluid flow in the device generated by alternating current electro-osmotic flow.

Bacteria present through the entire depth of the channel inside a microfluidic system can be captured efficiently through tailoring the orientation of the 3D electrode and by creating a dielectrophoresis force field cage (Cheng et al. 2007). In a study by Cheng et al. (2007), the authors demonstrated that their microfluidic device is capable of sorting and collecting three different types of pathogens (Figure 2) at a rate of ~300 particles/sec through 3D electrodes.



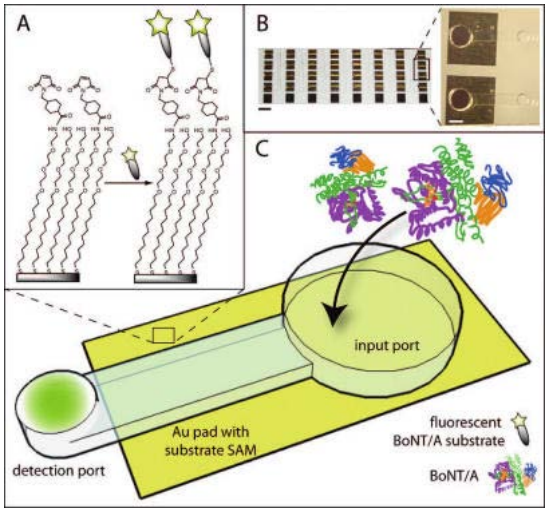
Microfluidic chip for trapping and detecting *E.Coli* in biological samples

Figure 2. (a) Image of the four stages of the integrated chip from the inlet to outlet. (b) The entire chip consists of a 25 µm high, 1 mm wide, and 14.5 mm long channel, enclosed by two glass slides. The individual outlet channels are 25 µm high, 350 µm wide, and 5.5 mm in length. Electrodes were fabricated on both glass slides, creating a 3D electrode system. Reproduced with permission from Cheng et al. (2007).

Deliberate or accidental contamination of food or drink with *Botulinum* neurotoxin (BoNT) is a form of bioterrorism and a concern for homeland security. The current method of detection is through mouse bioassay which is sensitive, but slow, expensive, low throughput, and requires sacrificing animals. The Centers for Disease Control and Prevention, Atlanta and the National Center for Food Protection and Defense, St. Paul along with researchers from the University of Wisconsin-Madison have developed a microfluidic platform with high sensitivity, on-site potability and multiplexing capabilities for reliable *Botulinum* Neurotoxin Detection in solution (Frisk et al. 2009; Frisk et al. 2007). The developed device consists of input and detection ports interconnected by a microchannel (Figure 3). The toxin sample is applied into the input port to catalyze the cleavage reaction of the fluorescent labeled peptide. The cleaved fluorescent labeled fragment diffuses into the detection port designed to facilitate evaporation of the solution and effectively preconcentrate analyte before fluorescence detection. This evaporation led to 3-fold signal amplification over 35 minutes. The first generation of device (Frisk et al. 2008) used a fluorescent substrate tethered to silica beads with relatively low sensitivity. In the second generation of device (Frisk et al. 2009), the detection sensitivity was

improved by tethering the substrate to a self-assembled monolayer on a gold surface and this device was able to detect as little as 3 pg/mL of the toxin in buffer.

Miniaturized microfluidic versions of macroscopic assays such as sandwich type immunoassays (Moorthy et al. 2004) and Förster Resonance Energy Transfer (FRET) fluorescence-based endopeptidase assays (Mangru et al. 2005; Sun et al. 2009) provides clear advantages over conventional technologies including the ability to operate in semiautomatic mode and a reduction of reagent consumption, facilitating field deployment.



Microfluidic sensor for *Botulinum* neurotoxin detection in vegetable soup

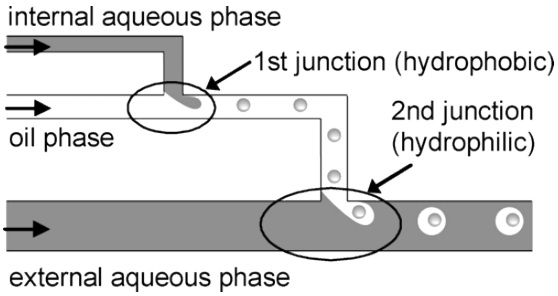
Figure 3. Sensor schematic: (A) Self Assembled Monolayers (SAM) formation on Au yields mixed monolayers of amine- and hydroxyl-terminated alkanethiols presenting the BoNT enzymatic substrate. (B) PDMS microchannels on 40 arrayed Au pads (10.5 mm^2) with inset image representing two neighbouring channels. (C) BoNT is added at input port and incubated on SAMs, during which time it can cleave the immobilized substrate, releasing fluorescent fragments into solution. Flu-labeled fragments are concentrated at detection port via evaporation. Reproduced with permission from Frisk et al. (2009).

Food Processing In food and bioprocessing industries, microfluidics has the potential to generate new products and processes by influencing food microstructure and thereby the rheology and functional properties of the final product. The laminar flow phenomena in microfluidic systems facilitates pressure-driven and electro-kinetic flow of fluids in microchannels and thus provide a powerful platform for DNA sequencing, polymerase chain reaction (PCR) and immunoassays.(Sia and Whitesides 2003). The solvent extraction in a microfluidic chip is expected with higher efficiency due to shorter diffusion distance and relatively large interface area between water and organic streams inside the microfluidic channels. Researchers have used microfluidic chips for solvent extraction of bioactive compounds from plant based products such as strychnine (Tetala et al. 2009).

In the food and dairy industry, liquids and solids are mixed and blended for several reasons including dispersing gums and stabilizers in ice cream mix or dairy products; and for dissolving salt and sugar in water to make brines. The characteristics such as fluid viscosity, fluid density, laminar/turbulence nature of fluid flow plays a key role in an effective mixing. Microfluidics can address the challenge of mixing liquid-liquid and

liquid-solids effectively (Beebe et al., 2002; Skurtys and Aguilera, 2008). As an example, Microfluidics International Corporation, Newton has developed and is selling multiple stream mixer reactors and food processors for the production of highly concentrated nanoemulsions, nanosuspensions, nanoencapsulations and nanodispersions.

Oil-in-water and water-in-oil food emulsions such as mayonnaise and margarine respectively can be industrially produced by introducing energy through physical means in a mixer equipment, leading to shearing strains which will break up to form one phase into the other. Microfluidic devices have the potential to dispense chemicals in a controlled manner at the scale of droplets to tailor the properties of foams and emulsions (Skurtys and Aguilera 2008; Zwan et al. 2006). For preparing double emulsions, Okushima et al. (2004) have used two T junctions in a series. Figure 4 shows the microfluidic arrangement to produce a water-oil-water double emulsion. The aqueous drops to be enclosed are formed periodically upstream at the first junction where the internal surface of the channel is hydrophobic. At the downstream junction where the surface is hydrophilic, organic droplets enclosing the aqueous droplets are formed. By changing the flow rates and the wetting properties of the micro-channels, the authors have demonstrated the formation of variuos types of emulsions with different droplet sizes.



Droplet formation in microchannel networks of a microfluidic device

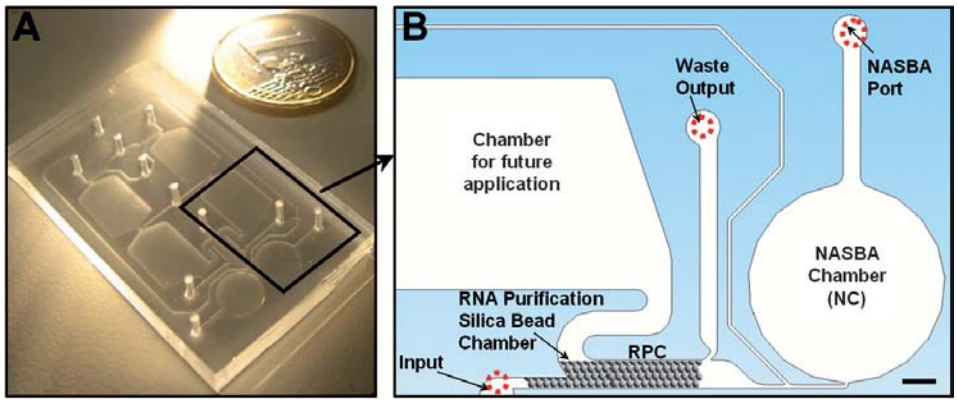
Figure 4. Basic concept for preparing double emulsions (W/O/W) using T-shaped microchannels. Reproduced with permission from Okushima et al. (2004).

Animal Science The microfluidic technology presents itself as a novel tool for solving problems in animal science and veterinary industry by bringing the benefits of miniaturization, integration and automation. Integration of microfluidics, MEMS (micro-electro-mechanical systems) and biological systems, a new class of systems called BIOMEMS, can help to deliver drugs to specific locations of the animal systems (Scott 2005). BIOMEMS incorporates sealed channels, wells, fluidic ports and electrodes for delivery and analysis of cells, DNA and biomolecules. Smart disease treatment delivery system will contain sealed packages of the molecular coded drugs to be delivered to specific parts of the animal system (Meng et al. (2009); Receveur et al. (2006))). This will help the farmers to reduce the costs of veterinary medicine and manage the health of livestock effectively by minimal usage of drugs.

Bovine mastitis is the inflammation of the mammary gland in cows and is a major concern for the dairy industry as it lowers milk yield, reduces milk quality and increases production costs. Microfluidic technology has already been applied for the detection of mastitis in the animal production systems (Choi et al. (2006); Dimov et al. (2009); Lee at al. (2008); Moon et al. (2007); Ricco et al. (2009); Rodriguez and Galanaugh, (2007)). Rodriguez and Galanaugh (2007) have designed a novel microfluidic slide assembly using

wedge design to detect or quantify leukocytes in milk for the purpose of disease detection and cell counting.. The milk sample is mixed with a meta-chromatic substance to stain the leukocytes. The somatic cells are distributed evenly in the chip by capillary action and the stained cells are identified using fluorescence microscopy. This device has the advantage of having different reaction chambers, allowing the milk to be mixed with the dye. Lee et al. (2008) have developed a biochip that incorporated DNA amplification of genes that are specific for seven known mastitis-causing pathogens. Dimov et al. (2008) have developed a similar microfluidic device (Figure 5) that integrates solid-phase extraction and nucleic acid sequence based amplification (NASBA) for the identification of low numbers of *E. coli*. By integrating and incorporating microfluidics to biochips, it is possible to determine several targets on one platform, which can improve assay efficiency, specificity and sensitivity for better mastitis detection and treatment.

Blue4Green, a spin-off company from the University of Twente, The Netherlands is marketing a lab-on-a-chip system for testing animal blood or urine in the pasture to provide reliable veterinary diagnostics. This microfluidic system has the capability to measure the concentration of a number of minerals in blood or urine with capillary electrophoresis. Li et al. (2004) has designed a microfluidic-based health monitoring device in a lollipop (Lollylab system) using saliva as sample for disease monitoring, pregnancy testing, hormone monitoring, detection of virus and strep throat infection in livestock animals, and monitoring of medications, . The chip is embedded with a candy shell that includes saliva stimulants. The chip accepts saliva and or delivers fluids from ports that become exposed as the candy shell is dissolved in the mouth of animal. A drug reservoir with an electronically controlled microejector is also included in this device for timed drug delivery.



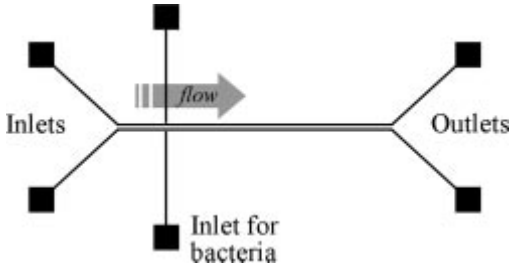
Microfluidic device for RNA purification and point-of-care molecular diagnostics

Figure 5. Integrated microfluidic RNA purification chamber and real-time NASBA device. (A) Photograph of the device. The microfluidic architecture is mirrored to allow for 2 separate reactions with the same reagents, but different samples, to incorporate controls. (B) Single device architecture showing the distinct functional microfluidic modules: RNA purification chamber (RPC) and real-time NASBA chamber. The remaining channels and chambers have been included for future integration of on-chip lysis. All channels and chambers are 80 mm high. Scale bar is 1 mm. Reproduced with permission from Dimov et al. (2008).

Microfluidic technology is also effectively used in animal science for simplifying in-vitro fertilization procedures for livestock breeding. Wheeler et al. (2006, 2007) have developed a microfluidic system that physically sorts the sperm and eggs by controlling the flow of gases or liquids through a series of channels and valves. It is possible for breeders to use this technology to rapidly sequence the genomes of cattle, poultry, pig and sheep by considering the traits such as disease resistance and leanness of meat. The effect of delivery of pharmaceuticals, and feed supplements to the livestock can be precisely monitored and or delivered through microfluidics technology.

Plant Production Systems The unique ability of microfluidic devices to produce concentration gradients can be coupled with advances in fluorescent substrates for studying enzyme reactions and for collecting high quality and comprehensive measurements on a wide variety of plant responses by system biologists (Hansen et al. 2003).

Bacteria *Xylella fastidiosa*, known for causing diseases in grapes, citrus, coffee, almond and alfalfa plants lives inside the xylem vessels of the plant host. Currently there are no effective methods to prevent or control the diseases caused by *Xylella fastidiosa*. To investigate and characterize the bacterial plant pathogen's molecular and biochemical aspects of infection processes and strategies, Fuente et al. (2007), Meng et al. (2005) mimicked the plant xylem vessel using microfluidic chambers. Polydimethyl-siloxane (PDMS) microfluidic chambers (100um wide, 100 um wide and 14 cm) (Meng et al. 2005) showed that the migration of *X.fastidiosa* cells is directionally controlled against rapidly flowing currents of growth mediumwhich helped to understand the colonization behaviour and migration of cells inside plant vascular systems. A pilus is a hairlike appendage found on the surface of bacteria. Pili connect a bacterium to another species or build a bridge between the interior of the cells for functions such as transfer of plasmids to provide antibiotic resistance. In understanding the role of pili in contributing to the adherence of *X. fasitdiosa*, traditional methods such as parallel-plate flow chambers, atomic force microscopy and laser tweezers had difficulty in obtaining data measurements due to large size of the chamber, and time consumption. The microfluidic chambers (Figure 6) designed and fabricated by Fuente et al. (2007) are useful and convenient for assessing the drag forces necessary for detaching bacterial cells from a glass substratum. The shear forces generated by flow through the microfluidic device was used to assess the degree to which two distinct pilus types, influence adhesion of bacteria to the glass substratum. The advantages of the microfluidic chamber devices over macroscale flow chambers includes provision of a larger dynamic range of shear forces, a platform that is readily integrated with microscopy and an efficient system that can be assembled to mimic nano-and microscale features of plants.



Microfluidic chamber design for characterizing bacteria

Figure 6. Schematic of the basic microfluidic chamber design. Microfluidic channels were 80 µm wide, 50 µm in depth, and 3.7 cm in length. Reproduced with permission from Fuente et al. (2007).

Glucosinolates are important natural products that occur in cruciferous plants, and have anticancerous propeties due to the enzyme modulation behavior. Fouad et al. (2008) used microchip capillary electrophoresis method to qualitatively determine glucosinolates from Arabidopsis thaliana seeds. The method, which utilizes microchip with fluorescence detection, circumvents the multistep procedures of conventional methods. The microchip was fabricated in poly(methyl methacrylate) and comprises of interconnected network of fluid reservoirs and microchannels. This study has demonstrated that microfluidics is an effective tool for metabolomics, and targeted metabolic profiling applications.

Zhang et al. (2006; 2007), have developed a microfluidic approach to generate capsules of biohydrogels at room temperature with good control of particle size distribution and internal structure. Microcapsules with hydrogel shells that are formed by biopolymers are used for the encapsulation and controlled release of pesticides or fertilizers. Hence, microfluidics is an enabling analytical technology for crop-based agriculture. Ko et al. (2006) have designed and fabricated a PDMS-based microfluidic channel for cultivating tobacco protoplasts. The results of this study demonstrated that the microfluidic devices are novel in the field of plant cell engineering and cell analysis.

Agilent Technologies, Santa Clara is commercially selling a microfluidics based platform called Agilent 2100 Bioanalyzer for sizing, quantification and quality control of DNA, RNA, proteins and cells on a single platform. Food and grain industries have widely adopted this microfluidic based technology for defect identification such as sulphur deficiency and bug damage in wheat grain (Uthayakumaran et al. 2007). A device in the format of CD with microfluidics has been created (Peng et al. 2007) to rapidly identify pathogens in the crops. Plant diseases from fungal, bacterial and viral organisms was rapidly identified by Wang and Li (2007) using a microfluidic microarray assembly in which flexible probe array creation and fast DNA sample hybridization were conducted in microchannels.

The companies involved in producing and commercializing microfluidic systems and devices for applications relevant to agriculture, food and bioprocessing industries are listed in Table 1.

CONCLUSION Microfluidics is an important enabling technology that uniquely integrates various research areas for a broad range of scientific and commercial applications. The market for the Lab-on-a-chip microfluidic systems is enormous as the

technology has demonstrated sufficient benefits for the food, agriculture and biosystems industries. Factors impeding the growth of the microfluidics market are slow adoption rate by the consumers and the lack of standards. Dedicated to research applications, microfluidics products are rather produced in low volume. The penetration of microfluidics to the agri-food and biosystems market will require the technology validation from a manufacturability point of view, and addressing the knowledge gap in framing the standards. There is a need to improve the existing microfluidic technologies that are too complicated or expensive to integrate into a functional system. The new tools and devices have to perform at greater accuracy levels and higher levels of throughput than standard macro-scale automated equipments. To progress beyond the laboratory and out into everyday world to solve problems of the agriculture, food and bioprocessing industries, microfluidic technology has to overcome scaling issues for increasing throughput using multistep processing, multiplexing and parallelisation strategies. Nonetheless, the room for growth, opportunities and innovation for microfluidic applications in the agri-food and biosystems industries is enormous.

Acknowledgements The authors gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada and the Manitoba Health Research Council for funding support.

Table 1. Companies producing and commercializing microfluidic devices and systems for applications in agri-food industries.

Company Name and Location	Technology/Application	Website Address
Affymetrix Inc., Santa Clara, CA, USA	Biochips for sequencing the genomes of cattle that relate to commercially valuable traits such as disease resistance and leanness of meat	http://www.affymetrix.com
Agilent TechnologiesInc., Santa Clara, CA, USA	Microfluidic platform (Bioanalyzer 2100) for sizing, quantification and quality control of DNA, RNA, proteins and cells. Example application includes quantifying the relative amount of fractions proteins in soybean cultivars	http://www.agilent.com
Akonni Biosystems Inc., Frederick, MD, USA	Gel-drop microarray platform for diagnosis of diseases and extracting nucleic acids from animals	http://www.akonni.com
Arryx, Inc., Chicago, IL, USA	BioRyx 200 is used to collect specified types of cells from a mixed suspension, manipulate cells for enhanced viewing, with applications in animal breeding	http://www.arryx.com/
Blue4Green, Enschede The Netherlands	Microfluidic based hand-held tool for analysis at the point of animal care	http://blue4green.com/
Caliper Life Sciences Inc., Hopkinton, MA, USA	LabChip GX platform for high throughput screening and predictive assessments of biological and food product quality	http://www.caliperls.com
Dupont, Wilmington, DE, USA	Qualicon food safety sensor for testing food-borne bacteria using capillary electrophoresis	http://www2.dupont.com
Epigem Ltd, Redcar, UK	Fluence microfluidic chips for biochemical monitoring of food, soil and water	http://www.epigem.co.uk
Fluidgm Corporation, San Francisco, USA	Microfluidic-based EP1system for validating single-nucleotide polymorphism for testing cattle health	http://www.fluidgm.com

Integram Plus Inc., UK	Microfluidic Pesticide Biosensor	http://www.integramplus.com
Lc Sciences, Houston, TX, USA	µParaflo microfluidics technology and microRNA discovery, detection and profiling for animals and plants	http://www.lcsciences.com
LioniX BV, Enschede, The Netherlands	Integrated optics and microfluidics based products for genomics, proteomics, cellomics for plants and animals	http://www.lionixbv.nl
Microfluidics International Corporation, Newton, MA, USA	Microfluidizer high shear fluid processor, food processing applications	http://www.microfluidicscorp.com
Microfluidic Systems, Fremont, CA, USA	M-Band product offers biodefense, toxin or airborne pathogen detection and identification	http://www.microfluidicsystems.com/
Micronit, Enschede, The Netherlands	Glass based lab-on-a-chip products for monitoring nutrients, and to sort plant cells to increase crop quality and production	www.micronit.com
miniFAB Pty Ltd, Victoria, Australia	Uses nano-bio-films to a microfluidic chip and incorporating it into a complete system for diagnostics. Examples include a device for detecting eye diseases by analyzing nanoliter tear samples of animals	http://www.minifab.com.au
Nanoterra, Inc., Cambridge, MA, USA	Portable analytical systems for food safety monitoring, pathogen detection in water, and for creating monodisperse droplets, foams, and colloids in food industries	http://www.nanoterra.com
NSG Precision Cells, Inc., Farmingdale, NY, USA	Quartz based microfluidic chips for use with micro-pumps, and other micro-machines with applications in chromatography and electrophoresis analysis	http://www.microfluidicchip.com
VitaeLLC, Madison, WI, USA	Microfluidic devices for culture, study, and manipulation of cells and embryos in assisted reproduction of livestock and cattle	http://www.vitaellc.com
XY Inc., Fort Collins, CO, USA	XY sex-selection technology (control of all sperm sorting) in non-human mammals, including cattle, horses, pigs using flow cytometry	http://www.xyinc.com/

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