Plant miniature greenhouse

Huawei Jiang\textsuperscript{a,1}, Xinran Wang\textsuperscript{a,1}, Maneesha R. Aluru\textsuperscript{b,\textsuperscript{*}}, Liang Dong\textsuperscript{a,\textsuperscript{*}}

\textsuperscript{a} Department of Electrical and Computer Engineering, Iowa State University, Ames, Iowa, USA

\textsuperscript{b} School of Biological Sciences, Georgia Institute of Technology, Atlanta, Georgia, USA

\textbf{A R T I C L E   I N F O}

Article history:
Received 6 June 2019
Received in revised form 26 July 2019
Accepted 23 August 2019
Available online 24 August 2019

Keywords:
Plant chip
Microfluidics
Greenhouse
Miniaturization

\textbf{A B S T R A C T}

We report on the development of a miniature greenhouse for large-scale phenotyping of \textit{Arabidopsis thaliana} plants. This greenhouse is capable of flexibly creating and varying a set of environmental conditions including temperature and light intensity through electronic circuits. The device uses light emitting diodes as light source, combines a thermoelectric cooler and a heater to fine tune the internal growth temperature, and uses a liquid crystal shutter to allow automatic imaging from outside of the device when needed. We demonstrate utility of the miniature greenhouse in conjunction with a vertical plant chip to continuously monitor both the vegetative and reproductive growth of wild-type and the immutans mutant of \textit{Arabidopsis}. In addition, the phenotype and growth timeline of plants grown within the miniature greenhouses are highly comparable to previously published reports. Thus, this newly developed device can serve as a powerful platform for large and multi-scale level phenotyping of \textit{Arabidopsis} plants with sufficient throughput, and under environmental conditions critical for plant growth.

© 2019 Elsevier B.V. All rights reserved.

1. Introduction

Understanding the plant phenome is a difficult and challenging process. This is because the phenotype of a plant is influenced not only by its genetic makeup but also by many developmental and environmental factors. External stimuli such as quality and quantity of light, temperature, humidity, carbon dioxide and nutrient availability, play critical role(s) in shaping the overall phenotype of a plant from seed germination to seed development [1–9]. The model plant \textit{Arabidopsis thaliana} has an exceptionally small genome, but even it has tens of thousands of genes in its genome [10–13]. Although several genetic tools and high-throughput large-scale genomics studies have been reported for \textit{Arabidopsis}, such large-scale quantitative studies of plant phenotypes for characterization of the whole plant phenome are severely lacking [14–20].

Conventional phenotypic analyses of plants grown either on soil or on agar plate suffer from low spatial and morphological resolution at the millimeter scale, and low throughput [21–34]. Microfluidics offers an attractive alternative to generate large-scale phenotype data in a high throughput manner with improved data statistic, and at reduced costs [35]. Although previous studies demonstrate the benefit of using microfluidics on whole multicellular organisms such as \textit{Drosophila melanogaster} and \textit{Caenorhabditis elegans} [36–38], many such devices for plant phenotype analyses were focused on characterizing one plant organ or the other and/or one particular growth condition [39–46].

We had previously reported on the development of a vertical and transparent microfluidic device capable of phenotyping \textit{Arabidopsis thaliana} plants at the whole organismal level [47]. Phenotyping of \textit{Arabidopsis} seed germination and plant growth was performed for approximately 2 weeks under one specific light and temperature conditions. Here, we extend these studies and report on the development of a miniature greenhouse for phenotyping \textit{Arabidopsis} plants up to 30 days. This greenhouse can be used in conjunction with the vertical plant chip, and incorporates new features such as varying light intensities and temperature conditions, two critical environmental factors governing plant phenotype. Moreover, both vegetative and reproductive phases of \textit{Arabidopsis} plant growth can be monitored in real-time within the same device in a high-throughput manner. To the best of our knowledge, plant phenotype measurements at different environmental conditions has not been achieved previously using microfluidics technology.

\textsuperscript{*} Corresponding authors.

E-mail addresses: maneesh.a.aluru@biology.gatech.edu (M.R. Aluru), ldong@iastate.edu (L. Dong).

\textsuperscript{1} These authors have an equal contribution to this work

https://doi.org/10.1016/j.sna.2019.111572
0924-4247/© 2019 Elsevier B.V. All rights reserved.
2. Design of miniature greenhouse

2.1. Design overview

A miniature greenhouse is designed to control environmental conditions for plants growing on the plant chips. This greenhouse shown in Fig. 1a consists of three main parts: a growth chamber, a temperature controller, and a light intensity controller.

The growth chamber has the dimensions of 3.25"(width) × 7.5"(height) × 3.5"(depth). The front side of the chamber has a window covered by a polymer dispersed liquid crystal (PDLC) film (Smart Tint, Inc., USA). Because the PDLC film can be switched between a transparent and an opaque state by applying or removing a voltage, it allows us to take pictures for plants from outside of the growth chamber, as shown in Fig. 1b and c. To obtain good thermal isolation and increase light intensity, the inner walls of the other three sides are covered with heat reflective insulating materials (Heatshield Products, Inc., Escondido, CA, USA).

Inside the growth chamber, there are a mini fan, a support rack, a plastic holder, a light-emitting diode (LED) ring, and a plant chip.
The mini fan is used to realize good air circulation for achieving fast cooling and heating within the chamber. The obtained temperature near to the plant chip is found to have a minor temperature variation of less than 2°C. The LED ring is used to provide light for the chamber. The light intensity can be easily controlled by adjusting voltage. The ring arrangement of the LEDs is suitable to provide a relatively uniform light intensity. The light intensity falling on the Arabidopsis seeds is found to have less than 5% difference across the seeds loaded into the plant chip. A temperature sensor and a light intensity sensor are installed inside the growth chamber to track temperature and light conditions, which will be introduced in the circuit control section below.

2.2. Circuit control system

The flow chart of the circuit control system is shown in Fig. 2a. As mentioned before, there are two sensors in the growth chamber. The SHT11 temperature sensor (SENSIRION, Inc., Switzerland) is chosen due to its high accuracy, small size, and high speed. A photodiode (PDB-C142, Advanced Photonix, Camarillo, CA) is used as the light intensity sensor due to its low price, small size, and high accuracy. These two sensors detect the environment conditions and achieve data indicating the temperature and light intensity within the growth chamber, and then feed these data to the central controller, i.e., Arduino UNO board (ARDUINO, Inc.). The Arduino UNO is a microcontroller board based on the ATmega328. It has 14 digital input/output pins (6 of which can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, and a USB connection. Besides, it is able to support SPI, I2C, and UART TTL serial communication and contains all necessary function needed to support the microcontroller. The Arduino UNO board connects to a computer with a USB cable or power up with an AC-to-DC adapter or battery. The central controller receives data coming from the sensors, and then analyzes data. On the other hand, according to the analyzing results, the central controller also sends out commands to other specific control circuit boards to adjust the environmental temperature and light intensity within the growth chamber.

It should be noted that our plant growth experiments are conducted above and below the room temperature. Because a normal resistive heater can only increase temperature above the room temperature, a thermoelectric or Peltier cooling plate is chosen to work as both heater and cooler. The Peltier device is a plate-type element consisting of arrays of P-type and N-type semiconductors. If the direct current is supplied to the plate, one side surface generates heat and increases the local temperature, while the other side surface absorbs heat and decreases the local temperature. Therefore, changing the direction of the current supplied to the Peltier device allows for the heating and cooling operations. Therefore, a current direction control circuit is designed as shown in Fig. 2b and c. The circuit provides an electric current for the Peltier cooling plate attached at the bottom of the chamber. An H-bridge circuit is used to control the current direction. Six MOSFETs are used, two of which are P channel (IRF5305PB, a dual MOSFET) and others are N channel (IRL2703PB, a dual MOSFET). These MOSFETs are positioned like in Fig. 2b, so that a full H-bridge control can be achieved with two I/O pins of the Arduino UNO board.

By combining the microcontroller unit (MCU), the temperature sensor, and the Peltier plate, it is possible to obtain an accurate temperature control system. Its working process is described as follows. At the beginning, the temperature sensor gets the temperature data, and then the MCU compares this data with a pre-set value. If the current temperature within the chamber is higher than the pre-set value, then the MCU will write “1” and “0” to the two I/O pins connected to the two edge N channel MOSFETs. This indicates that one N MOSFET is opened, and the other one is closed. For example, if the left N MOSFET is opened and the right one is closed, then the current will flow through the Peltier plate from left to right. If the current is inversely, then the Peltier will function as a cooler to decrease the temperature within the growth chamber. However, when the temperature within the chamber is lower than the pre-set value, the MCU will write “0” and “1” to the two I/O pins, thus, the working process is inversely.

The control method for light intensity is similar to the temperature control method mentioned above. The only difference is that instead of using the above-mentioned H-bridge to change the current direction flowing through the Peltier plate, we use the switches to control turning the on/off states of the LEDs. As a matter of fact, in our control system, switches are just the name, since the I/O pins of the Arduino UNO board can play the roles. According to the datasheet of the Arduino UNO board, the high output voltage of its I/O port is 3.3 V, high enough to turn on LED. For high efficiency and saving I/O ports, 6 LEDs are connected to one I/O pin. As the LED ring used in our case contains 18 LEDs, three I/O pins are needed to control the light intensity. To get a uniform light intensity, the 18 LEDs are positioned like in Fig. 2d. The LEDs with the same uppercase letter are connected together. The working process is the same as the temperature controller, i.e., using the data obtained by the photodetector to decide the number of LEDs in the ON state. Of course, when a high light intensity is needed or the output voltage of the I/O pins is not high enough to turn on the LEDs, an external power can be added into this control system. In that case, the switches will be replaced by the indeed switches, such as relays, and also, the I/O pins on the Arduino UNO board will just provide a “turn-on” signal like in the temperature control system.
2.3. Characterization of miniature greenhouse

Within the growth chamber, the highest temperature of 86.4 °C is found at the heater. On the plant chip, the highest temperature is 42.5 °C and the lowest temperature is 14.8 °C. The highest light intensity is $581 \, \mu E \, m^{-2} \, s^{-1}$ (31.4 $\times 10^3$ Lux) and the lowest light intensity is $10.7 \, \mu E \, m^{-2} \, s^{-1}$ (5.8 $\times 10^2$ Lux). To measure the stability, the Arduino UNO board is connected to the computer through the USB cable, and then the data collected by the sensors can be saved through the Integrated Development Environment (IDE) based software to program the Arduino board. The testing result is shown in Fig. 3a. The pre-set value is 25 °C. From the plot, it is seen that after a few minutes, the temperature gets close to the pre-set value, and the variation is within ±4%. The response time is defined as the time the system needs to reach a new stable state when the temperature changes. In our testing, the temperature is changed from $23 \pm 0.6$ °C to $29 \pm 0.9$ °C. The result is shown in Fig. 3b. According to the testing result shown in the inset curves of Fig. 3b, the device needs less than 1 min to increase or decrease 5 °C, which is considered fast for the plant growth application. The temperature
oscillation observed in Fig. 3 results from the dynamic cooling or heating process of the Peltier plate to maintain the temperature stable within ±4% of the pre-set temperature point.

2.4. Preparation of plant chip

The plant growth chip is fabricated as described previously [47] using a conventional soft lithography technique [48] to create a master mould for microfluidic channels. Briefly, a mixture of polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning, USA) and its curing agent with a weight ratio of 10:1 is poured onto the master mould and then cured on a hotplate at 90 °C for 1 h. Then, the hardened PDMS polymer is peeled from the master mould and bonded to a microscope glass slide (75 mm × 50 mm × 0.9 mm) through oxygen plasma treatment. The inlet and outlet ports of the device are manually punched with a mechanical puncher.

Wild-type (WT) and the immutans mutant (im) of Arabidopsis thaliana were used to assess utility of the newly designed miniature greenhouse. Preparation of plant growth medium, and Arabidopsis seeds are as described previously [47]. Following loading and stratification of the two types of seeds in seed holding sites [47], plant chips are vertically placed in the miniature greenhouse(s) (shown in Fig. 1b). The growth medium is initially loaded into the plant chips. A mini peristaltic pump is placed outside the growth chamber to deliver more growth medium into the chips through tubing when the water level drops below the roots of the plants. Plant growth is monitored for 6–28 days under different light intensities and temperature conditions. Due to the hydroponic growth, relative humidity (RH) inside the chamber is found to be above 70% RH. But, no damage to electronics is observed at the end of the growth experiment. Various phenotypic characteristics of the growing plants such as root and hypocotyl length, and leaf number are recorded and analysed. A microscope (MZ205, Leica, Germany) with a video camera (QICamera, QImaging, Canada) mounted on a programmable robotic arm (UR10, Universal Robots, Denmark) is used to image plant growth in the greenhouse. All data points reflect an average of at least three replicates.

3. Results and discussion

3.1. Arabidopsis phenotype under varying light conditions

Light intensity plays a very critical role in the overall growth of a plant. To test light control of the newly designed miniature greenhouse for plant phenotyping studies, we monitor growth of wild-type and the immutans mutant of Arabidopsis under four different light intensities (0 μE m⁻² s⁻¹, dark; 10 μE m⁻² s⁻¹, low light; 100 μE m⁻² s⁻¹, normal light; and 200 μE m⁻² s⁻¹, high light). Individual greenhouses are maintained at a specific light intensity and plant chips(s) loaded with Arabidopsis seeds are placed in these greenhouses. Seeds are allowed to germinate and grow for 4 weeks, at a constant temperature of 22 °C. Consistent with our previous report [47], Figs. 4 and 5 show that under normal light conditions (10 μE m⁻² s⁻¹), both WT and immutans seeds germinate between 24–30 h. This timeline appears to be true also for seeds germinating under a range of light conditions, except for immutans seeds.
Fig. 6. Root length of (a) WT and (b) immutans at four different light intensities. Histograms comparing root length of WT and immutans at different light intensities (c) 0 μE m⁻² s⁻¹; (d) 10 μE m⁻² s⁻¹; (e) 100 μE m⁻² s⁻¹; (f) 200 μE m⁻² s⁻¹.

Arabidopsis plants have been shown to grow more vigorously under higher light intensities when compared to low light conditions [49,50]. The results presented in this paper are also similar to previous reports with maximum overall growth observed for wild-type Arabidopsis plants growing under normal to high light conditions (100–200 μE m⁻² s⁻¹), whereas under dark/low light conditions (0–10 μE m⁻² s⁻¹) growth is either very slow or inhibited (Fig. 4). Overall growth of immutans plants is similar to wild-type Arabidopsis under low light conditions (0–10 μE m⁻² s⁻¹), but they grow more slowly under normal light conditions (100 μE m⁻² s⁻¹) when compared to WT, and do not reach the reproductive stage (formation of flowers and siliques) even after 29–30 days (Fig. 5). Moreover, immutans exhibits a significantly stunted growth pattern at 200 μE m⁻² s⁻¹, suggesting that the mutant is

germinating under dark/low light conditions - under these conditions the germination is slightly shifted to between 30–42 h. It should be noted that immutans seeds were allowed to germinate for 1–2 days under low light conditions before transferring the plant chips to different light intensities. This is because immutans does not germinate or germinates poorly under normal light conditions.
experiencing very high light conditions even at 200 μE m⁻² s⁻¹. Significant inhibition of plant growth, similar to immutans at 200 μE m⁻² s⁻¹, was also observed for WT plants growing under a higher light intensity of 500 μE m⁻² s⁻¹ (data not shown). While the cotyledons of WT seeds germinating under all light intensities are green in color, those germinating under dark are yellow due to the lack of the green chlorophyll pigment [51]. Green colored cotyledons and leaves were also observed for immutans plants grown under low light (10 μE m⁻² s⁻¹) but not for plants grown under normal light (100 μE m⁻² s⁻¹). As expected, these have the white/green variegated phenotype typical for the immutans mutant [52,53].

Light also has a strong effect on root growth and previous studies report a rapid increase in root growth in response to higher light intensities [54]. In agreement with these studies, our studies show that root length for wild-type Arabidopsis increases steadily almost by a factor of 3–4 under normal/high light conditions when compared to dark/low light conditions (Fig. 6). In contrast, different growth light intensities had little influence on the growth of WT hypocotyl except for those grown in dark (Fig. 7), which were longer.
Fig. 8. (a) Emergence and number of leaves observed for WT and immutans during the growth period at different light intensities (10 μE m⁻² s⁻¹, 100 μE m⁻² s⁻¹, and 200 μE m⁻² s⁻¹). (b) Histogram comparing number of leaves observed between WT and immutans during growth period at the same light intensities as in (a).

Fig. 9. Growth of wild-type Arabidopsis (a) and immutans (b) in the miniature greenhouse(s) set to a constant light intensity of 100 μE m⁻² s⁻¹ and in combination with different temperature conditions (<15 °C, and at 23 ± 2 °C, 30 ± 2 °C, and 42 ± 2 °C). Wild-type and immutans seeds were germinated and grown in vertical plant chips placed in miniature greenhouses for up to 8 days.
Fig. 10. Root length of WT and immutans (a) grown under normal light at different temperature conditions. Histograms comparing root length of WT and immutans (b) $T < 15 \, ^\circ C$, (c) $T = 23 \pm 2 \, ^\circ C$, and (d) $T = 30 \pm 2 \, ^\circ C$.

Fig. 11. Hypocotyl length of WT and immutans (a) grown under normal light at different temperature conditions. Histograms comparing hypocotyl length of WT and immutans (b) $T < 15 \, ^\circ C$, (c) $T = 23 \pm 2 \, ^\circ C$, and (d) $T = 30 \pm 2 \, ^\circ C$. 

as expected [51]. Growth of *immutans* hypocotyl is similar to WT whereas the roots are shorter than WT (Figs. 6 and 7). In addition, there was a significant difference in the number of leaves emerging under different light intensities for both types of plants (Fig. 8). The first two leaves for WT emerged earlier than 180 h under 10, 100 and 200 μE m⁻² s⁻¹, while such a phenotype was only observed for *immutans* plants growing under 10 μE m⁻² s⁻¹. These results are highly comparable to previous reports on slow growth of *immutans* plants versus WT [52,53].

3.2. Arabidopsis phenotype under varying temperatures

Temperature is another critical factor in plant growth with photosynthesis and growth rising up to an optimum temperature, beyond which growth declines steadily but significantly [49,55]. The typical growth range for *Arabidopsis* is between 16–25 °C, with an optimum temperature of 22/23 °C. Therefore, we determined the effect of a range of temperatures (15 °C, low; 23 ± 2 °C, normal; 30 °C, high; 42 °C, very high) on *Arabidopsis* growth phenotype using the miniature greenhouse. Individual greenhouses were set at specific temperature and plants were grown up to 8 days in chips at a constant light intensity of 100 μE m⁻² s⁻¹. At normal temperature of 22–23 °C, and up to 30 °C, both WT and *immutans* seeds germinate by 30 h (Fig. 9). However, the germination was delayed at low temperatures (15 °C), and seeds did not germinate even after a week of incubation at 42 °C.

Similar to the results obtained under different light conditions, root growth appears to be significantly influenced also by temperature (Fig. 10). Root length increased with the rise in temperature from 15 °C (low) to 23 °C (normal), but slowly decreased at 30 °C (high) for both types of *Arabidopsis* plants [55]. As expected for growth under normal light conditions, length of the hypocotyl increased with rising temperatures with significant growth observed at 30 °C for both types of plants (Fig. 11) [56]. One problem we encountered is that while cotyledons of WT plants grown under temperatures ranging from 15–30 °C were all green in color, cotyledons for *immutans* plants were always observed to be white except at normal temperatures of 22–23 °C (Fig. 9) perhaps due to the sensitivity of *immutans* to higher light and temperature conditions [52,53]. *Immutans* seedlings are known to give rise to variegated or white/albino cotyledons when germinated and grown under normal to high light/temperature conditions (100 μE m⁻² s⁻¹). These albino plants do not grow further and eventually die without giving rise to leaves.

To better assess and compare the effect of temperature on growth phenotype(s) of WT and *immutans*, we germinated and grew both WT and the mutant under different growth temperatures while keeping the light illumination constant at 10–15 μE m⁻² s⁻¹; under these light conditions *immutans* gives rise to green cotyledons and leaves. Similar to results observed in Fig. 5, low light in combination with normal and high temperature conditions give rise to green cotyledons both in WT and *immutans* mutant (Fig. 12). However, the germination is significantly delayed (WT) or inhibited (*im*) under low light/low temperature conditions, indicating the importance of a synergistic interaction between light and temperature for seed germination [57,58]. Root length was optimum at 23 °C and slowly tapered off at 30 °C in WT even under low light conditions, whereas it remains similar between different tempera-

---

**Fig. 12.** Growth of wild-type *Arabidopsis* (a) and *immutans* (b) in miniature greenhouse(s) set to a constant low light intensity of 10–15 μE m⁻² s⁻¹ and in combination with different temperature conditions (less than 15 °C, at 23 ± 2 °C, at 30 ± 2 °C).
Fig. 13. (a) Root length of WT and immutans grown under low light at different temperature conditions. Histograms comparing root length of WT and immutans (b) $T = 23 \pm 2^\circ C$, and (c) $T = 30 \pm 2^\circ C$.

Fig. 14. (a) Hypocotyl length of WT and immutans grown under low light at different temperature conditions. Histograms comparing hypocotyl length of WT and immutans (b) $T = 23 \pm 2^\circ C$, and (c) $T = 30 \pm 2^\circ C$. 
tures in imputans in comparison to normal light conditions which it is reduced by almost a factor of 2 at 30 °C (Figs. 10 and 13).

The Arabidopsis hypocotyl elongation is known to be under the control of environmental factors such as light and temperature, and also various plant hormones [56,57]. Such an interplay between these factors becomes easily noticeable in the imputans mutant at higher temperatures (30 °C). Whereas hypocotyl length does not change significantly for WT Arabidopsis with changing temperature(s) under low light conditions, hypocotyls of imputans plants grown under low light/high temperature (30 °C) show the phenotype of plants grown in the dark (Fig. 14). Studies show that temperature-dependent hypocotyl elongation is mediated by the plant hormone indole-3-acetic acid (IAA) in normal light-grown Arabidopsis, and that this growth response is significantly reduced in seedlings containing reduced levels of IAA [8]. It has also been shown that rice imputans mutants have a significant up-regulation of IAA compared to WT [59]. Although more detailed studies are necessary, our results suggest that perhaps IAA levels may play a role in the hypocotyl phenotype observed for the Arabidopsis imputans mutant.

4. Conclusions

Microfluidic devices provide powerful platforms to interrogate multicellular organisms at the organismal level. Our previous work led to the development of a vertical plant chip that was capable of phenotyping germination and growth of multiple Arabidopsis thaliana seeds in real-time. However, monitoring the growth and phenotyping of Arabidopsis plants under more than one environmental growth condition had not been achieved thus far. The developed miniature greenhouses can flexibly change the environmental conditions such as light intensity and temperature. Furthermore, the use of liquid crystal shutter allows for taking images easily from outside of the devices when needed without interrupting plant growth. We also demonstrate Arabidopsis growth in the plant chip for 8–30 days, thus extending the utility of this plant chip for both vegetative and reproductive growth of Arabidopsis plants. By integrating plant chip(s) with the miniature greenhouse technology, we have developed a powerful experimental framework for high-throughput, large-scale growth and phenotyping of Arabidopsis thaliana plants with different genotypes, and environmental conditions critical for plant growth. In addition, to realize a more powerful miniature greenhouse, one could consider incorporating different types of sensors inside the growth chamber and plant chip. For example, integration of nutrient sensors [60,61] into the plant chips will facilitate studying nutrient use efficiency of plants, while biosensors [62,63] can provide information on plant growth in different biological environments directly created inside the plant chips. In addition, inexpensive electronic nose and infrared sensors [64–66] could be integrated into the miniature greenhouse for studying of photosynthesis and volatile organic compounds emitted from plants.

Acknowledgements

This work was supported by the U.S. National Science Foundation under Grant number DBI-1353819, and the Plant Sciences Institute at Iowa State University.

References


Biographies

Dr. Huawei Jiang received her Ph.D. degree in Electrical Engineering from Iowa State University (Ames, IA, USA) in 2016. She previously received her M.S. degree in Chemical Engineering from Dalain University of Technology (Dalian, China). Currently, she is a Post-Doctoral Research Associate in the Laboratory for MEMS and Biochips at Iowa State University. Her research is mainly focused on the development of miniature sensors and microsystems for environmental monitoring, sustainable agriculture, and biomedicine.

Dr. Xinran Wang received her Ph.D. degree in Electrical Engineering at Iowa State University (Ames, IA, USA) in 2019. She previously received her B.S. degree in Electronic Science and Technology from Wuhan University (Wuhan, China) and M.S. degree from Wuhan Institute of Physics and Mathematics, China Academy of Sciences (Wuhan, China). Her research interests include sensors, electronics and biochips for sustainable agriculture and biomedicine. She joins EnGeniusAg LLC (Ames, IA, USA) in Fall 2019.

Dr. Maneesha Aluru is a Senior Research Scientist in the School of Biology, Georgia Institute of Technology (Atlanta, GA, USA). She previously worked as a Research Assistant Professor, Associate Scientist and Postdoctoral Research Associate at Iowa State University (Ames, IA, USA). She has a PhD in molecular biology from New Mexico State University, and received the MSc and PhD degrees in molecular biology from Iowa State University and New Mexico State University, respectively. Her research interests are in functional genomics and systems biology.

Dr. Liang Dong is currently a Professor in the Department of Electrical and Computer Engineering at Iowa State University (Ames, IA, USA). He is also affiliated with the Department of Chemical and Biological Engineering (as Professor by courtesy), the Microelectronics Research Center (as Associate Director), and the Plant Sciences Institute (as Faculty Scholar) at Iowa State University, as well as the U.S. DOE’s Ames Laboratory (as Associate). He previously worked as a Postdoctoral Research Associate in the Department of Electrical and Computer Engineering at University of Wisconsin–Madison (Madison, WI, USA). He received his Ph.D. degree in Electronic Science and Technology from the Institute of Microelectronics at Tsinghua University (Beijing, China) and B.S. degree in Precision Instrument from the School of Mechnano- Electronic Engineering at Xi’an University (Xian, China). His research interests include MEMS/NEMS, sensors, actuators, optical devices, microfluidic devices, and micro/nanoscale manufacturing, and their applications in sustainable agriculture and environments, plant science, biomedicine, and internet of things. His research has been recognized by the Best Student Paper Award at IEEE Nanotechnology Conference (2017), the Best Conference Paper Award Finalists at Transducers (2017), IEEE Nanotechnology Conference (2017), and IEEE Sensors Conference (2016). He was a keynote or plenary speaker on the topic of sensors-based plant and soil analytics at many major conferences such as µTAS (2017), PAC (2018) and Phenome (2019). He received the National Science Foundation CAREER Award, the PSE Faculty Scholar Award, the Early Career Engineering Faculty Research Award, the Harpole-Pentair Developing Faculty Award, the Warren B. Roast Undergraduate Teaching Award. He also was a recipient of the Top 100 National Outstanding Doctoral Dissertation Award of China (2007). He serves as Editor-in-Chief of Sensors and Actuators A: Physical, Associate Editor of Micro & Nano Letters, and Editorial Board Member of Scientific Reports and Journal of Nanomedicine.