Plant Nanobionics a Novel Approach to Overcome the Environmental Challenges

Mansour Ghorbanpour and Shohreh Fahimirad

Abstract Plant nanobionics is a new field of bioengineering that inserts nanoparticles into the cells and chloroplasts of living plants, which then alter or amplify the functioning of the plant tissue or organelle. The broader vision is to create a wide array of wild-type plants capable of imaging objects in their environment, self-powering themselves as light sources, infrared communication devices, and also function as self-powered ground water sensors. Plants are uniquely suited to perform such roles due to their ability to generate energy from sunlight and photosynthesis. In the field of nanobiotechnology, researchers want to develop bionic plants that could have better photosynthesis efficiency and biochemical sensing.

Keywords Plant nanobionics · Nanoparticles · Nanobiotechnology · Self-powering plants

Introduction

Nanoscale science and nanotechnology is the study and application of small sized objects range from 1 to 100 nanometers (nm), where novel characteristics make new and wide uses possible. Nanomaterials are therefore characterized as natural or engineered substances with at least one dimension in the size less than 100 nm. With quite diverse appearance, engineered nanomaterials can be spherical or near-spherical, tubular, or irregularly (non-spherical) shaped, which have been found in single, fused, and agglomerated forms with compositionally homogenous

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or heterogeneous (Hatami et al. 2016; Service 2003). There are many specific reasons that show why nanoscale has become so prominent; some of which are as follows (Mansoori 2017):

(1) Quantum mechanical (wavelike) characteristics of electrons inside matter are influenced by variations on the nanoscale. By nanoscale design of materials it is possible to vary their micro and macroscopic attributes including charge capacity, magnetization and melting temperature, without changing their chemical composition.
(2) A key attribute of biological entities is the systematic organization of matter on the nanoscale. Development in nanotechnology and nanoscience has allowed us to place man-made nanoscale things inside living cells (Ebrahimi and Mansoori 2014). It has also made it possible to study micro and macro structure of materials using molecular self-assembly (Xue and Mansoori 2010). This certainly is a powerful tool in materials science.
(3) Nanoscale components have unique properties such as very high surface to volume ratio, making them ideal for use in composite materials, reacting systems, drug delivery, and energy storage, etc.
(4) Macroscopic systems made up of nanostructures can have much higher density than those made up of microstructures. They can also be better conductors of electricity, resulting in new electronic device concepts, smaller and faster circuits, more sophisticated functions, and greatly reduced power consumption simultaneously by controlling nanostructure interactions and complexity.

Results of research and developments in the field of nanotechnology and nanoscience are entering into all aspects of our lives including, but not limited to, aerospace, defense, energy, environment, materials, manufacturing, medicine, agriculture and plant sciences (Ghorbanpour and Hadian 2015; Hatami et al. 2017; Ghorbanpour 2015; Baiazidi-Aghdam et al. 2016; Ghorbanpour and Hatami 2014; Hatami et al. 2014), etc. It is truly an atomic and molecular approach for building biologically, chemically and physically stable structures one atom or one molecule at a time. Presently some of the active nanoscience and nanotechnology research areas include nanolithography, nanodevices, nanorobotics, nanocomputers, nanopowders, nanostructured catalysts and nanoporous materials, molecular manufacturing, nanolayers, molecular nanotechnology, medicine such as Alzheimer's disease (Nazem and Mansoori 2008, 2014) and cancer (Ebrahimi and Mansoori 2014; Mansoori et al. 2007, 2010) prediction, prevention and treatment through nanotechnology), nanobiology, organic nanostructures to name a few.

Also, nanotechnology has the potential to enable new and enhanced functional properties in photosynthetic organelles and organisms for the enhancement of solar energy harnessing and biochemical sensing. Nanobionics engineering of plant function may contribute to the development of biomimetic materials for light-harvesting and biochemical detection with regenerative properties and enhanced efficiency (Giraldo et al. 2014). Thus, nanobionics aims to give plants superpowers.

Plant Nanobionics with Improved Photosynthesis Efficiency

Plant Nanobionic with Broaden Solar Light Absorption

In most kinds of plants, thylakoid membranes within chloroplasts are main location of the photosynthetic machinery. Chloroplasts are able to absorb visible range of the light spectrum which comprise of 50% of the incident solar energy radiation. Furthermore, Plants typically make use of only about 10% of the sunlight available to them (Zhu et al. 2010).

Thus, researchers have tried to improve photosynthetic efficiency by extending the range of solar light absorption (Blankenship et al. 2011).

Nanomaterials with perfect chemical and physical traits in chloroplast-based photocatalytic complexes form cause enhanced and new functional properties (Giraldo et al. 2014).

SWNTs are able to capture visible and near-infrared spectra of light wavelengths while chloroplast antenna pigments absorption rates are limited in this case.

Giraldo et al. (2014) successfully designed highly charged single-walled carbon nanotubes (SWNTs) coated with DNA and chitosan (a biomolecule derived from shrimp and other crustacean shells) which were able to spontaneously penetrate into chloroplasts. This new lipid exchange envelope penetration (LEEP) process for incorporating the nanostructures involves wrapping CNTs or nanoparticles with highly charged DNA or polymer molecules, enabling them to penetrate into the fatty, hydrophobic membranes that surround chloroplasts (Fig. 1).

Single walled carbon nanotubes (SWNTs) embedded within chloroplasts has the potential to enhance the light reactions of photosynthesis with their distinctive optical properties. SWNTs are able to capture visible and near-infrared spectra of light wavelengths while chloroplast antenna pigments absorption rates are limited in this case (Fig. 2). SWNTs convert this absorbed solar energy into excitons which transfer electrons to the photosynthetic machinery (Han et al. 2010).

Incorporation of CNTs into chloroplasts extracted from plants enhanced choloroplast's photosynthetic activity by 49% compared to the control. When these nanocomposites were incorporated into leaf chloroplasts of living plants, the electron flow associated with photosynthesis was enhanced by 30%. SWNT real-time sensing of NO in extracted chloroplasts and leaves could also be extended to detect a wide range of plant signalling molecules and exogenous compounds such as pesticides, herbicides and environmental pollutants.

Plant Nanobionic with Higher ROS Savaging Ability

Interestingly, SWNT-based nanosensors were able to monitor single-molecule dynamics of free radicals within chloroplasts for optimizing photosynthetic environmental conditions (light and CO_2) (Zhang et al. 2010).

Fig. 1 SWNT transport through chloroplast double membrane envelope via kinetic trapping by lipid exchange (Giraldo et al. 2014)

The major limitation in the use of extracted chloroplasts for solar energy applications is that they easily break down due to light- and oxygen-induced damage to the photosynthetic proteins. Giraldo et al. (2014) illustrated that cerium oxide nanoparticles (nanoceria) were combined with a highly charged polymer

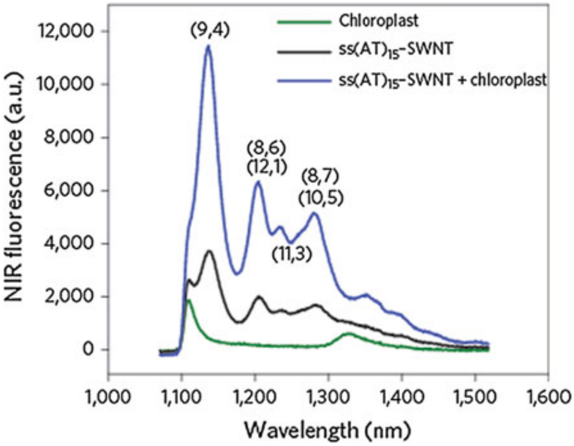

Fig. 2 Chloroplast autofluorescence was masked from near-infrared images by along-pass 1100 nm filter

(polyacrylic acid) pass through the outer membranes of the chloroplast and locate in the stroma, and remarkably prevent damage to the photosystems by quenching reactive oxygen species that are widely dispersed throughout the chloroplast and enable real-time monitoring of free-radical species and environmental pollutants using in vivo and ex vivo embedded nanosensors (Siddiqui et al. 2015) (Fig. 3).

In addition, solar energy is captured by chlorophylls in the two types of pigment-protein complexes (photosystems I and II, designated PSI and PSII,

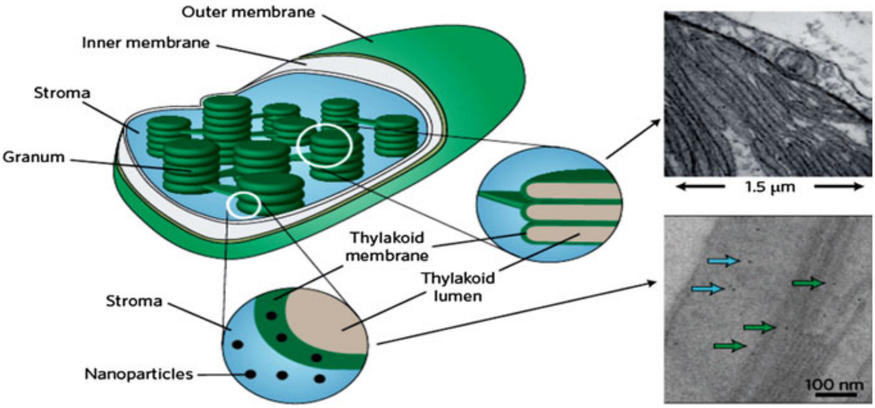

Fig. 3 Natural and nanobionic chloroplasts. The photosynthetic apparatus is mostly embedded in the thylakoid membranes of chloroplasts. Flattened thylakoids are stacked into grana, as shown by a micrograph of the cryptophyte alga *Proteomona ssulcata* (top right). The nanoparticles localize in both the thylakoid membrane and the stroma (bottom left schematic; green and blue arrows, respectively, in the bottom right micrograph) (Scholes and Sargent 2014)

respectively) and are converted into electrochemical energy to produce ATP and NADPH that are used for CO_2 fixation. PSII performs the light-induced oxygen evolution reaction and transfers electrons from water to plastoquinone in the membrane and PSI produces strong reducing power using electrons supplied by PSII and reduces ferredoxin and NADPH. Noji et al. (2011) illustrated that nanomesoporous silica compound (SBA) conjugated with photosystem II (PSII) maintained the high and stable oxygen-evolving ability of *T. vulcanus* PSII even inside silica nanopores. The activity lasted more than 3 h under the moderate illumination/dark cycles. Combination of PSII-SBA conjugates with the mediator recycling systems can remove the harmful effects of electron acceptors and light-induced radicals and have properties to develop for photosensors and artificial photosynthetic system.

Plant Nanobionic Designed as Detector for Various Chemicals Presented in Environment

Because the water evaporates, chemicals drawn up along with the fluid that don't easily vaporize get concentrated in the leaves. This means plants can detect very low concentrations of chemicals. Plant nanobionics has also enabled us to use plants as detectors for the presence of different chemicals in the soil and water, and even in the air. When one of these chemical compounds are present in the groundwater being absorbed and sampled naturally by the plant, the embedded carbon nanotubes will emit a fluorescent signal that can be read with an infrared camera that can be attached to a small computer similar to smart phone. The computer will then send an e-mail to the user.

Nanobionic Plant as Nitroaromatics Detector

It may seem exquisite but imitate from simple plant transpiration process. Plants draw up water and other analytes from the ground, and can accumulate even trace levels of analytes within tissues. Knowing this rule, Wong et al. (2016) made a nanobionic plant that can both detect explosives in groundwater and alert a user to their presence in the area. IR-fluorescent carbon nanotubes (CNTs) based sensors that selectively respond to nitro aromatics were injected into a spinach plant's leaves. These nanotubes quench in fluorescence intensity in the presence of nitroaromatics. Then a reference sensor that is invariant in signal intensity was designed. The plant draws the nitroaromatics or the common explosives component picric acid (2,4,6-trinitrophenol) up through the roots into its leaves, where the suppressed IR signal is imaged with a night-vision camera and sent to a smart phone via a WiFi signal. With the reference sensor embedded in the leaf as well, the technique produces high contrast images (Fig. 4).

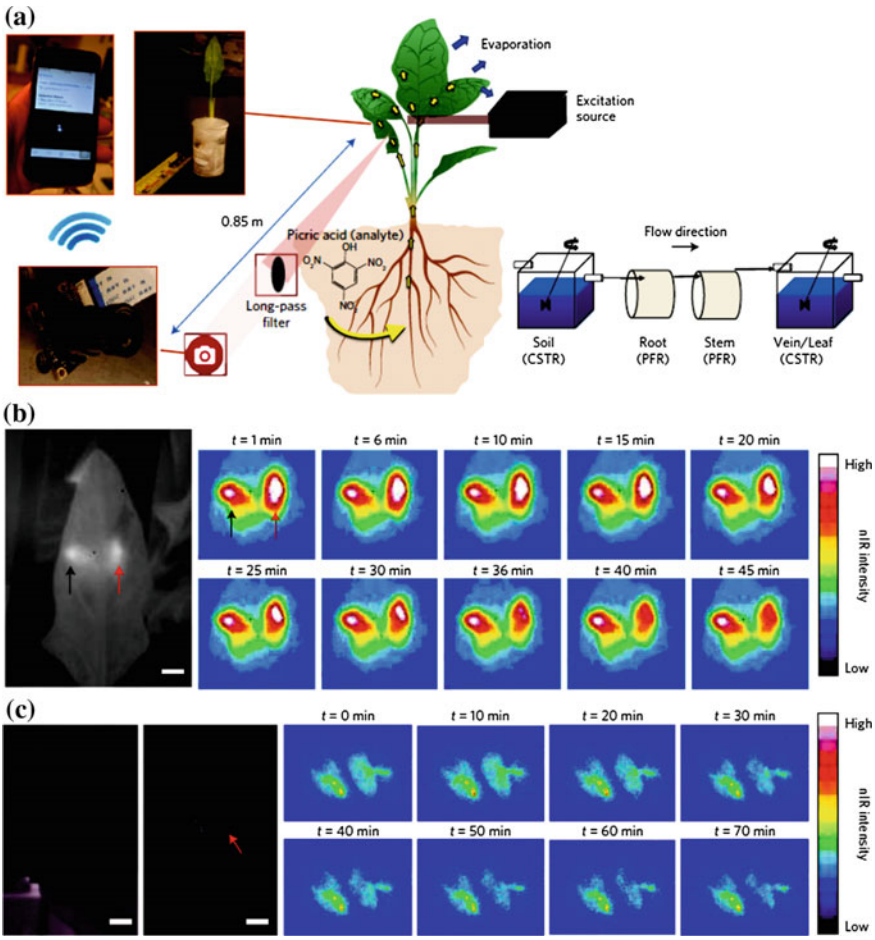

Fig. 4 Detection of picric acid using a nanobionic spinach plant. **a** Diagrammatic depiction of detection set-up with the nanobionic sensing plant shown here using a Raspberry Pi CCD detector (no infrared filters). **b** (Left) Bright-field image of spinach plant leaf infiltrated with SWCNTs and under 785 nm excitation. P-SWCNTs and B-SWCNTs indicated by black and red arrows, respectively. (Right) False-coloured time-lapse pictures show temporal changes in nIR fluorescence of a plant infiltrated with B-SWCNTs and P-SWCNTs as picric acid is transported from the roots to the leaves via the plant vascular system. While P-SWCNT nIR fluorescence remains stable, the B-SWCNT intensity drops as the leaf transpire a solution of picric acid (400-M) in 10 mM KCl. nIR images were taken with a Princeton Instruments OMA V InGaAs detector equipped with a 900 nm long-pass filter. SWCNTs inside leaves were excited with 785 nm laser incident at 15mW. Scale bar, 0.5 cm. **c** SWCNT nIR emission can be similarly detected by a Raspberry Pi CCD detector (infrared filters removed), which then transmit pictures wirelessly and in real time via an email interface to a smart phone. (Left) Bright-field imageof spinach plant infiltrated with SWCNT sensors. (Centre) nIR emission from embedded P-SWCNTs (black arrow) and B-SWCNTs (red arrow) is visualized with 785 nm laser excitation (15 mW). (Right) False-coloured time-lapse pictures similarly show temporal changes in nIR fluorescence of a plant infiltrated with B-SWCNTs and P-SWCNTs as picric acid is transported from the roots to the leaves via the plant vascular system. Scale bar, 0.5 cm (Wong et al. 2016)

Nanobionic Plant as Temperature Detector

Cyberwood was designed by employing a new synthetic carbon nanotubes which mechanical and structural properties resembling wood embedded and exquisitely sensitive to temperature changes into a matrix of plant cells from the tobacco. Preserving plant cells' natural ability to sense temperature variations even after their death cause electricity conductivity of this kind of carbon nanotubes change with temperature. The presence ofmulti-walled carbon nanotubes (MWCNTs) confers structural stability and a high electrical conductivity,which can be exploited to connect the samples to anexternal circuit (Di Giacomo et al. 2015). In fact, pectins and charged atoms (ions) play a key role in the temperature sensitivity of both living plant cells and the dry cyberwood. Pectins are sugar molecules found in plant cell walls that can be cross-linked, depending on temperature, to form a gel. Calcium and magnesium ions are both present in this gel. As the temperature rises, the links of the pectin break apart, the gel becomes softer, and the ions can move about more freely. As a result, the material conducts electricity better when temperature increases.

To synthesize cyberwood, several conventional nano-synthesis approaches were combined. At First step, undifferentiated tobacco BY-2 cells derived from the callus of seedlings of *Nicotiana tabacum* were cultured in a growth medium that contained MWCNTs. Spontaneous aggregation of cells was observed with tobacco cells combined with MWCNTs. After 24 h a gel-like material formed, was collected and dried at 47 °C for 15 d. The material formed had a complex, hierarchical structure, similar to wood (Fig. 5).

This construct it may find applications in thermal sensors, for example, for thermal cameras, or in distance sensors for consumer products and security systems Because of its exquisite temperature sensitivity. The cyberwood sensor can identify warm bodies even at distance; for example, a hand approaching the sensor from a distance of a few dozen centimeters. The sensor's conductivity depends directly on the hand's distance from the sensor (Fig. 6). The very high responsively to temperature changes of cyberwood suggests that it can be used as a temperature

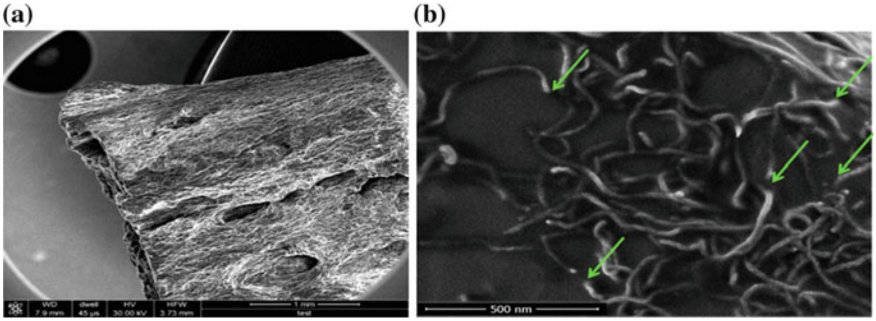

Fig. 5 **a** Low-magnification SEM picture of the cyberwood. **b** Top view of a cell wall of BY-2 with MWCNTs on top. Arrows emphasize some penetration points (Di Giacomo et al. 2015)

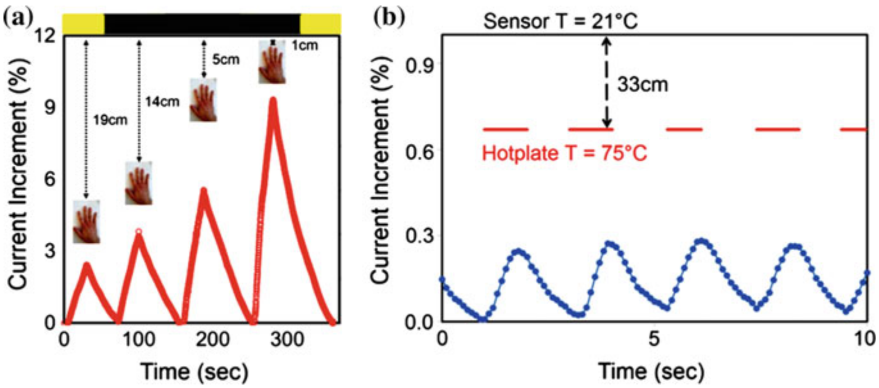

Fig. 6 Cyberwood as a thermal distance sensor. Plots show variations of the current in different cyberwood samples, as a function of the position, in- andoff-axis, of heat-emitting bodies in time. **a** Larger sample detecting the position of a hand. **b** Microsample detecting the position of a hotplate (Di Giacomo et al. 2015)

distance sensor. The distance of a warm body from the sensor can be inferred from temperature measurements performed at constant environmental conditions (Di Giacomo et al. 2015).

Conclusion and Future Prospects

Utilization of nanoparticles to create nanobionic-plant-enabled sensors for environment monitoring is a novel complex strategy. The researchers' interest to design creative nanosensors give real-time information from a plant is growing sharply. The product of this kinds of researches will Make human dreams of carrying a plant speak about their surroundings to a reality. Researchers are trying to increase the number of sensors that can be applied to plants and enhance chemicals detections in both the air and groundwater by plants. Monitoring plant signaling pathways of pest infestations, damage, and drought while being capable to real-time analysis will be a new revolution in agriculture industry. It is not far to have commercial sensing plants in home send messages directly on smart phone data about temperature, humidity and pollutants.

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