

Plant-based Biosensors: Harnessing biotechnology for environmental monitoring

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ABSTRACT

Plant-based biosensors have become an innovation for environmental monitoring. They combine the natural sensing abilities of the plant with modern synthetic biology and genetic engineering. These biosensors have the ability to detect stimuli (physical, chemical, biological) and convert them into measurable electrical, optical or biochemical signals. Recently, developments have been made in genetically encoded plant-based biosensors (GEBPs), protein engineering, and synthetic biological circuits which are resulting in improved sensitivity and versatility for monitoring environmental conditions and responses from plant stress. Applications of these biosensors include sustainable agriculture, environmental monitoring, and plant bioengineering. The challenges related to biosensor design, signal reliability, and large-scale deployment still remain. Future research should explore the intersection of synthetic biology, advanced receptor engineering and engineered living materials to develop more sensitive, adaptive plant-based biosensors for sustainable agriculture and real-time environmental monitoring.

Keywords: Plant-based biosensors, environmental monitoring, synthetic biology, GEBPs, sustainability

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Introduction

Environmental pollution, climate change, and increasing agricultural challenges have made plants as a food source, vulnerable to scarcity. This situation demands for a monitoring system which can help monitor the plants stress signals according to the environment. Different technologies could be used for this purpose which includes optical/fluorescence sensors, electrochemical sensors, and genetically encoded biosensors. All these technologies work on their specific properties to detect stress signals. Biosensors should be preferred because they provide high sensitivity and specificity, being rapid and cost-effective while allowing real-time monitoring and without harming the plant [1].

Biosensors are the devices which use transducers to detect the specific target molecules and convert these biological responses to measurable signals. These devices have gained attention because of their specificity, sensitivity, and quick response [2]. Plants are considered a good choice for biosensors because of their immobile nature. They are constantly facing environmental changes and have developed their own sophisticated and precise sensing mechanisms. Plants can naturally detect different kind of stimuli (physical, chemical, biological). This stimulus detection is helpful in detecting different stress signals. As plants are naturally able to detect changes, researchers have started engineering them for natural sensing mechanisms for environmental monitoring, making plants suitable for using as biosensors [3].

Scientists don't use the whole plant for monitoring purposes. Instead, they engineer their genes, proteins, promoters and reporters in order to develop biosensors. Genetically encoded plant-based biosensors (GEBPs) are genetically engineered biosensors which are the result of modifying natural sensing mechanisms of plants. Unlike the conventional biosensors, these biosensors use genes and proteins in order to receive and respond to different physical, chemical, and biological signals. And they work inside the living plant cells and monitor real time changes occurring in the plants [4].

Synthetic biology has carved the path for scientists to develop genetically modified plants and to use them as biosensors. Synthetic biology helps in developing these biosensors by using protein engineering, function screening, reprogramming native molecular switches and detecting new specific molecules. This is how GEBPs are being created and then further being used to monitor plant stresses, detect measurable signals and then provide with the measurable signals [5]. This genetic modification is very much needed in this era to attain sustainable agriculture and has application in environmental monitoring and plant biotechnology setting a foot in advance technology.

Working principles

Plants are sessile organisms. They remain at their place and can't move away from the stress and thus, they have evolved complex sensing mechanisms which help them to respond to their environment by detecting different kind of stimuli. These are the characteristics of plants which make them fit for biosensor development. Plant biosensors convert these responses into detectable signals by detecting different kind of stimuli [6]. Plant biosensors consist of different components. The 1st one is the sensing element which detect any stimuli (pathogen, pollutant, chemical, or any stress factor). The 2nd component is a promoter which receives the signals from the sensing element and develops the gene expression. 3rd component is reporter gene which produces different kind of biological signals such as color change, fluorescence, or luminescence. Now comes the 4th component, the transducer, converting biological signals into optical, electrical or electrochemical signals. This component is important for measurement and analysis. [7]. The signal transduction process, in which the biological signal is detected and converted into a measurable output, starts with the exposure to an environmental stimulus e.g. heavy metal, drought, pathogen etc. Then plant receptor comes forward and identifies the stimulus. This leads to the starting of signal transduction process as the signals move through the plant cells. Then the genes become activated for their expression. And in the end, a measurable output is produced which can be fluorescent proteins or electrical and optical signals [8].

Engineering of plant-based biosensors

Although plants possess one of the best sensing mechanisms, but still they are confined to sensing a limited type of stimulus. Their sensing abilities have evolved to recognize specific and limited compounds. Scientists wanted plants to detect new types of molecules and for this purpose they used synthetic biology. Synthetic biology combines biology and engineering to make modifications in plants according to the desired needs. Plants have proteins which are kind of natural detectors as they change their activity when a certain molecule binds to them. Scientists alter these proteins to make them able to recognize new compounds. For this purpose, protein engineering and functional screening is done and proteins are genetically modified according to the needs [9]. PYR1 is a plant receptor which detects the plant hormone abscisic acid naturally. Scientists have recognized its ligand binding site and made modifications in it in order to use it for new compounds which cannot be recognized by this receptor naturally. Other examples include cannabinoids and organophosphates which have been successfully modified for the detection of new molecules [10]. This advancement in biotechnology and environmental monitoring is very important as it sets a milestone in redesigning plant receptors and detecting new desired compounds. Engineered biosensors are becoming popular because of their accuracy, adaptability, sensitivity, and more

selectiveness. This concludes that engineering strategies have transformed plant biosensors into versatile analytical tools with their applications expanding in agriculture, pollution and environmental monitoring along with biotechnology.

Applications

Biosensors are extremely viable for environmental monitoring. They are used for detecting environmental pollutants, toxic chemicals, water impurities or contamination, and changes in quality of soil. This is how they help by detecting these changes and signaling us to do what is need to be done to prevent undesirable consequences. Pollution is one of the major environmental challenges we are facing today. Biosensors help detect pollution early, so that we can make our preparations to prevent it or reduce its harmful effects. Thus helping protect ecosystems by continuous monitoring. Biosensors, thus helps support conservation of environment [11]. Biosensors provide a great deal in detecting the biotic and abiotic stress. Abiotic stress such as drought, nutrient deficiency, salinity, temperature stress, and salinity can be detected earlier before the visible symptoms appear, helping earlier intervention. Biotic stress, on the other hand, can also be detected with these biosensors such as pathogens, bacteria, fungi, viruses, and insect attacks. Plants produce molecular responses when fallen prey to any of these stresses and engineered biosensors help detecting these responses. Early detection helping disease management, reducing crop loss, and help lowering pesticide use. [12]. As plant biosensors are continuously monitoring plant health, they are proven to be a great help for precision agriculture. They help monitoring of crop health, irrigation and fertilizer management and sustainable agriculture which leads to increase crop yield, reduce fertilizer waste and pesticide use, and resources can be used well. Apart from facilitating agricultural applications, plant biosensors are also used to monitor gene expression, study signaling of hormones, and understand cellular responses in a better way [13]. Because of all these applications, plant biosensors have become a valuable tool for agriculture, biotechnology, and environmental management.

Challenges

Plant biosensors are proven to be a great help to overcome environment and agriculture related challenges but with these benefits, there also come challenges and limitations. Biosensors are highly sensitive under field conditions and environmental interference makes it difficult to use them properly. Plant signaling pathways are sophisticated which is another hurdle for biosensor development. Engineering challenges and commercialization remain some more limitations for scientists to use plants as biosensors [14]. Plants also show plant-to-plant variability which results in different responses due to age, genotype and growth stage of the plant. Some plants may not be able to show response reversibility and will not be able to return to its original condition after stimuli disappears. Long-term stability is also a major challenge because plants may only work effectively for a short period of time and lose its performance over time [15]. Some sensing systems may not work in a different plant species because plants have different plant metabolic pathways. Data interpretation is also a major challenge as the responses shown from plants are mostly complex and can be aroused by multiple factors simultaneously, so a change may not always indicate one specific environmental factor [16]. These limitations require modern solutions and scientists are developing new technologies to overcome these solutions.

Future prospects

Although plant-based biosensing mechanisms have achieved a lot in recent years but there is still room for more advancements. Sensitivity and specificity of biosensors need to be improved. Synthetic biology techniques need expanding in order to achieve customizable biosensors and engineered receptors for targeting new and desired molecules. Molecular switches also need improvements to get desired outputs. In future, biosensors might be able to detect multiple stimuli all at once. Future biosensors have wide applications in climate-smart agriculture and precision farming. There is

also a need for early warning systems for environmental stress which can be accomplished by engineering biosensors. ELMs have a future in creating self-repairing sensing mechanisms, increasing durability, and support environmental remediation. Thus, integrating synthetic biology with biotechnology digital monitoring can help in making biosensors more versatile. Collaboration of synthetic biology with biotechnology and material sciences will bring advancements in biosensing mechanisms making them more advanced and according to our future needs. This will also help overcome technical limitations and more adoption in agriculture and environmental monitoring, contributing to sustainable development. Future holds new and great opportunities for biosensors making them practical tools for environmental protection.

Conclusion

Plant-based biosensors combine plants' natural sensing mechanisms with biotechnology and synthetic biology. They are new developing tools for environmental monitoring. Biosensors have provided several applications like environmental monitoring, precision agriculture and stress detection. Although there are still challenges including technical limitations, engineering complexity, field implementation, and need for further research but continued advances in synthetic biology, receptor engineering and engineered living materials are expected to develop plant biosensors. These biosensors have the ultimate potential to become important tools for continuous environmental monitoring and sustainable agriculture. In the upcoming years, it is possible to see plant biosensors bridging the gap between biological sensing mechanisms and practical environmental monitoring systems.

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