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Screen Printed Electrodes for Detection of Nutritional Content in Plants

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ABSTRACT

Flexible screen-printed electrodes (FSPEs) are electrochemical sensors made by printing conductive ink onto a flexible substrate such as polyester or polyimide. FSPEs can be programmed to detect a wide range of analytes, such as ions, gases, and biomolecules, making them useful sensors for a wide range of applications. They're commonly made utilizing screen-printing procedures, which entail transferring conductive ink via a mesh screen onto a flexible substrate. After drying and curing, the ink forms a durable conductive layer that can be utilized as the working electrode in an electrochemical sensor. To improve selectivity and sensitivity to certain analytes, FSPEs can be modified with specific sensing materials or coatings. FSPEs can be used to monitor plant nutrient levels in a variety of ways, including in situ sensing and distant monitoring. In situ sensing is the use of a handheld or portable electrochemical sensor to directly assess nutrient levels in soil or plant tissue. The usage of FSPE-based sensors that are incorporated into a wireless network and can offer real-time data on plant nutrient levels is used for remote monitoring. FSPEs provide various advantages over standard nutrient monitoring systems, including low cost, portability, and ease of use. FSPEs can also identify essential plant nutrients quickly and accurately, allowing for prompt action to treat nutrient deficits or excesses. However, FSPEs have several limitations, such as selectivity and sensitivity to specific analytes. To improve their selectivity and sensitivity to specific plant nutrients, FSPEs may require specific coatings or modifications. Furthermore, FSPEs may necessitate regular calibration to maintain accurate and repeatable results.

Keywords – Sensors, electrodes, sensitivity, plant nutrients

1.INTRODUCTION

Plant nutrient monitoring is an important feature of contemporary agriculture since it ensures optimal crop output while minimizing fertilizer consumption. Traditional nutrition monitoring approaches entail laboratory testing, which can be time-consuming, costly, and requires highly trained workers. As a result, simple, cost-effective, and dependable technologies for monitoring plant nutrient levels in real time are required. One promising approach to this problem is the use of flexible screen-printed electrodes (FSPEs) that allow for the rapid and sensitive detection of key plant nutrients such as nitrogen, phosphorus, and potassium. FSPEs offer several advantages over traditional methods of nutrient monitoring, including their low cost, portability, and ease of use. This article will provide a brief introduction to FSPEs and their applications in plant nutrient monitoring [1].

Flexible screen-printed electrodes (FSPEs) are a type of electrochemical sensor that is manufactured by printing conductive ink onto a flexible substrate such as polyester or polyimide. FSPEs can be designed to detect a wide range of analytes, including ions, gases, and biomolecules, making them versatile sensors for a variety of applications [1]. FSPEs are typically manufactured using screen-printing techniques, which involve the transfer of conductive ink through a mesh screen onto a flexible substrate. The ink is then dried and cured to form a stable conductive layer that can be used as the working electrode in an electrochemical sensor. FSPEs can also be modified with specific sensing materials or coatings to enhance their selectivity and sensitivity to particular analytes [1,2].

FSPEs have shown great potential in the detection of key plant nutrients, including nitrogen, phosphorus, and potassium. Nitrogen is an essential nutrient for plant growth, and its availability in the soil can have a significant impact on crop yield. FSPEs can be used to detect the concentration of nitrate and ammonium ions, which are the primary sources of nitrogen for plants. Phosphorus is another essential plant nutrient, and its availability in the soil can limit crop yield. FSPEs can be used to detect the concentration of phosphate ions, which are the primary source of phosphorus for plants. FSPEs have also been used to detect potassium ions, which are critical for plant growth and are involved in a variety of physiological processes, including photosynthesis and water regulation [1,2].

FSPEs can be used in various ways to monitor plant nutrient levels, including in situ sensing and remote monitoring. In situ, sensing involves the direct measurement of nutrient levels in the soil or plant tissue using a handheld or portable electrochemical sensor. Remote monitoring involves the use of FSPE-based sensors that are integrated into a wireless network and can provide real-time data on plant nutrient levels [1,2]. FSPEs offer several advantages over traditional methods of nutrient monitoring, including their low cost, portability, and ease of use. FSPEs can also provide rapid and sensitive detection of key plant nutrients, which can allow for timely intervention to address nutrient deficiencies or excesses [2,3].

However, FSPEs also have some limitations, including their selectivity and sensitivity to particular analytes. FSPEs may require specific coatings or modifications to enhance their selectivity and sensitivity to particular plant nutrients. Additionally, FSPEs may require regular calibration to ensure accurate and reliable measurements.

SPEs (screen-printed electrodes) are frequently utilized in electrochemical sensing applications such as plant nutrient monitoring. In comparison to standard electrode materials, SPEs have various advantages, including low cost, portability, and ease of production. We will examine the various approaches utilized in screen-printed electrodes for plant nutrition monitoring in this brief introduction [4]. Screen-printed electrodes (SPEs) provide a versatile and cost-effective platform for monitoring plant nutrient levels. SPEs can be manufactured with high precision and reproducibility using several techniques including as direct printing, inkjet printing, aerosol jet printing, and transfer printing. The technique used is determined by the application's specific needs, such as electrode shape, resolution, and material composition. SPEs can provide a reliable and portable solution for real-time monitoring of plant nutrient levels by employing these strategies [4].

The direct printing process employs a screen-printing machine, which normally comprises of a screen, squeegee, and ink reservoir. The screen is usually comprised of a mesh material that lets ink to flow through to the substrate, while the squeegee is used to press ink through the screen and onto the substrate. The ink employed in this process is often made up of conductive elements suspended in a binder or solvent, such as carbon, silver, or gold particles [1,4]. The inkjet printing technology use an inkjet printer that has been modified to handle conductive ink. A print head, ink cartridges, and a control unit are common components of a printer. The print head has small nozzles that deposit ink droplets onto the substrate, and the ink cartridges hold the conductive ink. This technique's ink is often made up of conductive nanoparticles or polymers suspended in a solvent [1,4]. The aerosol jet printing process employs an aerosol jet printer, which typically comprises of a pneumatic nozzle, ink reservoir, and control unit. The nozzle sprays a high-velocity stream of conductive ink particles onto the substrate via a gas flow. This technique's ink is often made up of conductive nanoparticles or polymers suspended in a solvent.

The transfer printing technique employs lithography machines, which typically include a mask aligner, spin coater, and developer. The mask aligner patterns the electrode design onto a photoresist-coated substrate, which is subsequently developed to generate the electrode pattern. The pattern is then transferred onto a polymer stamp, which is subsequently utilized to transfer the pattern onto the final substrate.

In terms of materials, the substrates used in these techniques can vary depending on the specific application. Common substrates include glass, plastics, and paper. Conductive materials used in the ink formulations include carbon, silver, gold, copper, and conductive polymers.

2. FABRICATION TECHNIQUES OF SCREEN-PRINTED CARBON ELECTRODE

Screen-printed carbon electrode combines working, reference, and counter electrodes in one design. This type of electrode provides a simple, portable, and disposable electrochemical measurement for sensing purposes. Since this electrode is disposable, the fabrication techniques should be able to facilitate fast mass production. Several fabrication techniques for Screen printed carbon electrode (SPCE) fabrication were reported in scientific papers. Most of them are using printing techniques (inkjet printing and screen printing) on flat substrate and the other was a coating technique. The screen-printing technique is a simple approach for SPCE fabrication. This technique is easy to follow by anyone without special expertise. In the screen-printing technique, three main components in SPCE fabrication including screen with electrode pattern, conductive ink, and squeegee-like part for spread the ink. The screen is available in various pore sizes. The screen is selected based on the particle size of conductive material for ink composition. The pore size of screen material should bigger than the particle size of conductive material. Several papers reported the use of a screen with a pore size of 36 mesh [5], 100 mesh [6], dan 200 mesh [7]

2.1 Preparation of the SPE

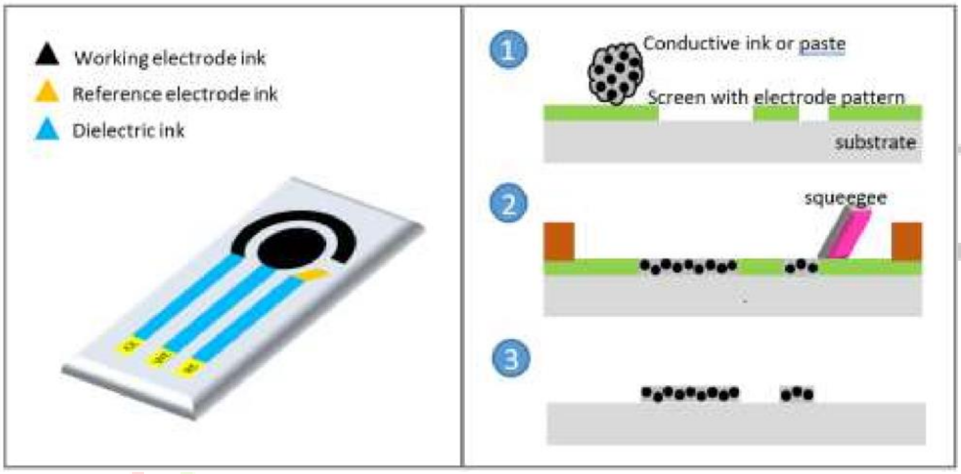

Figure 1. SPCE pattern and illustration of SPCE fabrication by a screen-printing technique.

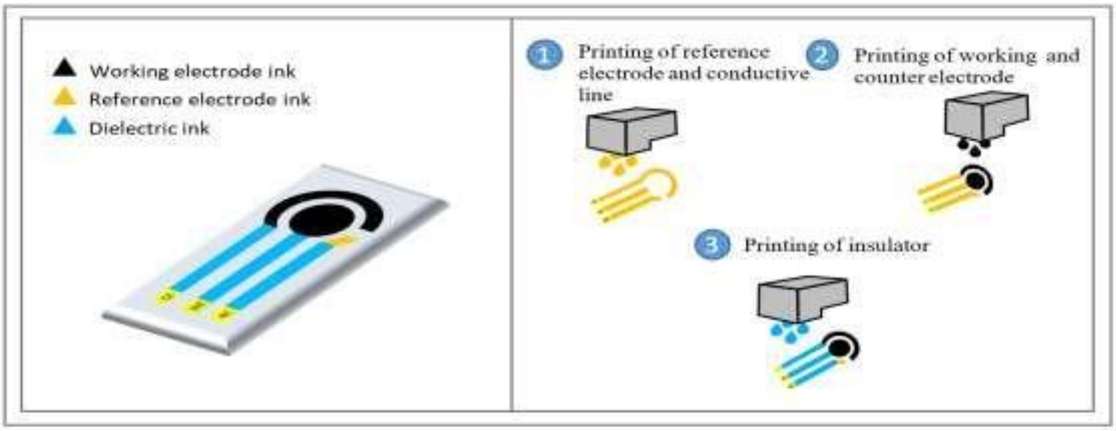

Figure 2. Pattern of SPCE and illustration of SPCE fabrication by inkjet printing technique (16)

The plan for fabricating SPCE using a screen-printing technology is shown in Figure 1. The procedure is as follows: 1) Place a screen with an SPCE pattern on top of the substrate; 2) Apply conductive ink to the top of the screen; and 3) Apply even pressure to the entire screen to disperse the ink evenly. To obtain a homogeneous SPCE surface from the screen-printing fabrication process, Step 3 is essential. Both flexible and stiff substrates could be used for SPCE fabrication using the screen-printing approach. For instance, Du and colleagues developed the fabrication of SPCE on PET (Polyethylene terephthalate) substrate [1] while Kit-Anan and colleagues employed screen printing technology for SPCE production on the Whatman paper filter [8]. In contrast, creating SPCE using inkjet printing technology results in more precise results. Ink dispensing can be precisely controlled thanks to inkjet printing technology. Additionally, compared to screen printing, the inkjet printing method uses less ink. Inkjet printing technology is utilised to fabricate SPCEs using a variety of printer types, such as the Fujifilm Dimatix Materials Printer ([9], [10], [11]), [12], [13], [8]), HP Deskjet D4260 ([14]), Epson EcoTank ET-2650, Epson Stylus Photo 1500W ([15]), and EPSON R230 ([3]) are some examples of inkjet printers.

Figure 2 shows the layout and plan for fabricating SPCE using an inkjet printing process. Computer-aided design (CAD) was used to prepare the electrode pattern, which was then transmitted to a printer that could produce the item quickly. Additionally, the nozzle was used to disperse ink from the cartridge onto the substrate ([16]). For ink dispensing, a number of processes are used, including piezoelectric ([17]), thermal ([18]), and electrodynamic ([19]). Due of its capacity to regulate size and printing speed, piezoelectric printing is chosen over other processes ([20]). SPT is the primary method applied for preparing the disposable electrochemical electrode. It is advantageous in the following aspects: (1) flexible design, which enables various patterns to be printed on the surface of the solid substrate as required; (2) allowing for semi-automatic/automatic batch production; (3) highly mechanized production, which can ensure the electrode stability and reproducibility; (4) a wide range of printing inks; (5) easy miniaturization, integration and array forming and (6) low production cost. Having the above merits, personalized SPEs can be manufactured following the researcher’s specifications on materials and patterns. With the development of biosensing technology, the demand for the SPE increased and some commercialized SPEs printed with different conductive materials emerged, such as Alderon Biosciences (USA), DropSens (Spain), Kanichi Research Service (UK) and Zensor (Chinese Taiwan) [21]. Comparatively, the DropSens SPEs are the most commonly used SPEs in electrochemical detection.

2.2 Drawback

The technique's drawback is that it can't reach tiny corners of the mould, which makes the printing appear sloppy. Contrarily, conductive ink is dispensed properly and with great accuracy when using fin inkjet printing. However, because of the extremely thin coating, the homogeneity of the manufactured electrode surface is low. Replication in the printing process is required in order to solve this issue. For the bulk production of SPCE, screen printing and inkjet printing processes are both used. Additionally, some articles ([10], [8], [22]) documented the combination of two procedures to acquire the desired features of SPCE that had been manufactured.

Drop-casting and drop-coating procedures are used in fabrication using coating processes. According to [23], [24] and [25], this method is frequently used to change electrodes and improve their electrochemical properties. Conductive ink is dropped onto the electrode surface and is then left there. In some instances, the masking process is used to create a specific coating pattern. Additionally, the drop coating technique could be used to examine the electrochemical characteristics of conductive substances.

3 ENVIRONMENTAL APPLICATIONS OF SPCE

Environmental monitoring is one application where screen-printed paper electrodes have demonstrated special value. The determination of pollutants such heavy metals [2], anions [26], or carbon nanostructures has been done using various types of paper impregnated with suitable reagents [27], modified with metal nanoparticles, or both in the absence or presence [28] of certain enzymes. Screen printed electrodes (SPEs) have attracted a lot of interest as adaptable and affordable instruments for a variety of environmental applications. SPEs have a variety of benefits thanks to their distinctive features and adaptable designs, such as portability, simplicity of use, and increased sensitivity. In order to address environmental issues, this article examines the various ways that screen printed electrodes are used in environmental monitoring, pollutant detection, biosensing, and other fields.

SPEs have transformed environmental monitoring by making it possible to analyse different metrics in real-time, on-site. To detect certain analytes including heavy metals, organic contaminants, and nutrients, these electrodes can be customised. They are useful for field measurements in soil, water, and air because they deliver quick results. SPE-based monitoring systems provide an economical and effective way to monitor environmental changes, enabling prompt resource management and decision-making.

Screen printed electrodes have become important resources for the detection of contaminants in various environmental matrices. SPEs have the ability to selectively capture and quantify target contaminants by functionalizing the electrode surfaces with particular recognition components, such as antibodies or aptamers. This adaptability makes it possible to detect a variety of contaminants, such as pesticides, poisons, and newly emerging pollutants. Biosensing applications have significantly advanced as a result of the incorporation of biological components with screen printed electrodes. The identification of biological targets, such as infections and biomarkers, is made possible by the modification of SPEs with enzymes, antibodies, or DNA probes. These biosensing technologies provide quick responses, excellent sensitivity, and minimal sample demands. SPE-based biosensors are used to improve monitoring capacities and protect public health in the fields of food safety, environmental microbiology, and the detection of waterborne pathogens. Electrochemical remediation strategies for the cleaning of the environment have showed promise when using screen printed electrodes. SPEs' large surface areas and adaptable construction make them ideal for electrochemical processes like electrocoagulation, electrooxidation, and electrochemical degradation. Heavy metals, chemical compounds, and dyes are just a few of the pollutants that can be treated using these procedures. SPEs support sustainable energy production from environmental sources in addition to monitoring the environment and implementing remedial measures. SPEs can utilise electrochemical processes to create useable electrical power, such as those found in solar or fuel cells. Applications for this feature include autonomous sensors, low-power environmental data collection devices, and remote environmental monitoring systems. SPEs monitor the environment and carry out corrective actions in addition to supporting environmentally friendly energy generation. SPEs can use electrochemical processes, such those used in solar or fuel cells, to provide usable electrical power. Applications for this capability include remote environmental monitoring systems, low-power environmental data collection devices, and autonomous sensors. The development of screen-printed electrodes (SPEs) as adaptable tools with tremendous environmental application potential.

4. CONCLUSIONS

For the detection of plant nutrients, flexible screen-printed electrodes (FSPEs) have proven to be incredibly promising electrochemical sensors. They are adaptable sensors for a variety of applications due to their capacity to detect a broad spectrum of analytes, including ions, gases, and biomolecules. FSPEs are made by screen-printing conductive ink onto flexible substrates, providing a low-cost and easily customized alternative. The effectiveness of FSPEs in detecting vital plant nutrients like nitrogen, phosphorus, and potassium has been proven. FSPEs can offer useful insights about the availability of nitrogen in the soil, a key factor determining agricultural productivity, by detecting nitrate and ammonium ions. The measurement of phosphate ions helps scientists estimate how much phosphorus is available, which can affect agricultural productivity. The crucial function that potassium ions play in plant growth and physiological activities is also monitored by FSPEs that detect potassium ions. In situ sensing and remote monitoring are the two main monitoring techniques enabled by these sensors. Utilising transportable FSPE-based sensors, in situ sensing involves the direct measurement of nutrient levels in soil or plant tissue. However, remote monitoring makes use of FSPEs that are built into wireless networks to deliver real-time information on plant nutrient levels, providing a convenient and effective monitoring solution over huge areas.

The benefits of FSPEs include their affordability, mobility, and simplicity of use, making a wide spectrum of users, from farmers to researchers, able to use them. FSPEs provide rapid and precise identification of vital plant nutrients, enabling immediate response in the event of nutrient surpluses or deficits. FSPEs show potential for a wide range of additional applications in agricultural and environmental monitoring in addition to their use in monitoring plant nutrients. Because of its adaptability and flexibility, FSPEs can be used to detect a wide range of analytes in addition to plant nutrients. They can be altered, for instance, to find pesticides, heavy metals, and other toxins in soil or water, assisting in the evaluation of environmental quality and guaranteeing the safety of agricultural products. FSPEs can also be used in precision agriculture to help farmers optimise their irrigation, fertilisation, and crop management techniques by providing real-time data on soil conditions. The creation of wearable and implanted sensors for tracking plant health and physiological responses is also made possible by FSPEs. Key indications including nutrient uptake, water stress, and disease progression can be monitored in real-time by incorporating FSPEs into wearable technology or embedding them in plant tissues. With the help of this information, early diagnosis and intervention can be facilitated, allowing for more specialised and effective plant management techniques.

In conclusion, FSPEs have demonstrated tremendous promise in the area of plant nutrient monitoring, providing a versatile, economical, and user-friendly solution. The monitoring and management of plant nutrient levels will be revolutionised by FSPEs with future improvements in selectivity, sensitivity, and calibration procedures, resulting in increased agricultural productivity and sustainable farming methods.

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