SOILMONITOR

Deliverable 6.4
First-Year Progress Report

Project Acronym:	SOILMONITOR
Project ID:	101097989
Dissemination Level:	Public
Due Date:	31.10.2023
Delivery Date:	31.10.2023
Delivery Type:	Report

Funded by the European Union

European Innovation Council

CAU
Christian-Albrechts-Universität zu Kiel

Prof. Dr. Martina Gerken
Telefon: +49 431 880 6250
E-Mail: mge@tf.uni-kiel.de

Table of Contents

1. The SOILMONITOR project

Eutrophication, shrinking biodiversity, and nitrate-polluted waters have brought fertilization practices in agriculture into public spotlight, highlighting the significant environmental and soil impacts of improper fertilization (Chen et al., 2023). This increase in attention is reflected in stricter regulations and laws, especially within the EU (e.g., Nitrates Directive 91/676/EEC; Federal Ministry of Food and Agriculture (BMEL), 2017; The Council of the European Communities, 1991) and urges for a better monitoring of soil nutrients.

In precision agriculture, the demand for data availability is growing as well, as informed decisions on agricultural processes are based on the evaluation of a proper database. Besides temperature and moisture levels, nutrient concentrations are of particular interest (Pierce & Nowak, 1999). Traditional methods of soil nutrient analysis are labour-intensive and often take between one and two weeks to deliver results. Therefore, a mapping of nitrogen dynamics and availability over the cropping period is in practice only possible with disproportionate effort. To address these problems, a novel sensor for automated soil water analysis is being developed within the SOILMONITOR project funded by the European Innovation Council (see Figure 1).

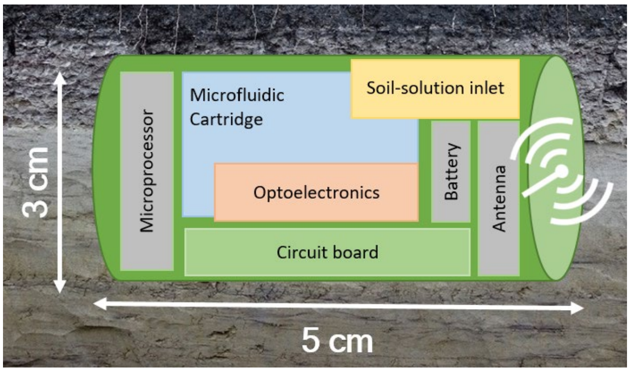

Figure 1: Schematic structure of the SOILMONITOR consisting of the three compartments energy supply (yellow), microfluidics (blue), control (gray).

The SOILMONITOR proposes a highly miniaturized sensor system for continuous monitoring of soil nutrients. Through time series monitoring of nitrate, phosphate, and ammonium, the SOILMONITOR is aimed at contributing to a balance in the supply of soil nutrients. The sensor is intended to spend one year maintenance-free in the soil, where it takes nutrient concentration measurements in soil water at regular intervals when there is sufficient soil moisture.

For this, soil water is drawn into a microfluidic through the ceramic of the inlet. In the microfluidic system, the solution is stained with a nutrient-specific assay and its concentration is determined by photometry using an organic light-emitting diode - organic photodetector (OLED-OPD) pair. Once the concentrations have been determined, the mixture will be pumped into a waste reservoir. The determined concentrations are to be sent to a station via a Lo-Ra WAN network. In the first development phase, nitrate will be measured; the measurements will then be extended to ammonium and phosphate.

2. Project scope

SOILMONITOR is a three-year EU-funded project that aims to develop a miniaturized sensor system for continuous monitoring of soil nutrients. The project is intended to deliver seven complementary and synergistic benefits: quick and informed decisions on fertilization, higher fertilizer efficiency, soil-quality improvements, easier compliance with environmental standards, reduced management efforts, less nutrient leaching, and reduced N_2O-emissions. The SOILMONITOR project is divided into six work packages aimed at the following main achievements:

- Development and optimization of a prototype to ensure the broadest possible applicability of accurate soil nutrient measurement, and test for these results.
- Development, test and optimization of water extraction and demonstration that the average sensor water extraction radius is equivalent to plant root water extraction radius.
- Demonstration of a maintenance-free sensor lifetime of at least one year.
- Preparation of private investment and/or funding (e.g., EIC Accelerator grant, Angel Investors) to transition and progress the sensor along the commercialization roadmap.

3. Technical progress

In the first year of the SOILMONITOR project work was carried out on the individual components necessary for the system.

3.1. Soil water extraction

Since photometric measurements require a water matrix, the first step is to extract soil water from the ground. Using a porous alumina ceramic, extraction experiments were conducted in preliminary tests for three soil types using a peristaltic pump. The easiest extraction was obtained for sandy soil, and the most difficult extraction for silt (Böckmann et al., 2021). These tests were extended to three types of well-specified typical test soils. It was found that a stronger suction is necessary for soil solution extraction in soils with a lower water content. The relation of pump size, system design and system cost are currently being investigated.

3.2. Photometric nutrient measurement

To test the suitability of the optoelectronic OLED-OPD pair chosen for the sensor, experiments with the well-known Griess assay (Griess, 1879) were performed for nitrate measurements. A good linear correlation for the concentration could be determined photometrically. The coefficient of determination here was 0.986 and the LOD was 46 µg/L (1.0 µM) (Titov et al., 2022a). Similarly, nitrate standard solution was measured based on the commercial Spectroquant (Merck) nitrate assay (Titov et al., 2022b). In the first project year we worked on achieving color-sensitive OPDs suitable for a differential measurement. We demonstrated that nanostructures may be integrated in the OPD stack for this purpose (Schardt et al., 2023). In parallel, the SOILMONITOR team is developing its own assay approach to match the OLED-OPD sensor system.

3.3. Design of microfluidic

In the SOILMONITOR project, we decided to fabricate microfluidic systems by photolithographic master design and replication in the silicone polydimethylsiloxane (PDMS). In this method, a silicon wafer is coated with a negative photoresist and structures are selectively cured with UV light via a photomask. The uncured photoresist is dissolved with the aid of a developer, thus producing a positive for casting with silicone. This process is particularly suitable for producing microstructures in one plane. The structures are sealed with a glass lid that will later include the OLED-OPD measurement system. A multi-level approach will be used for liquid storage. In the first project year, the process was established and inlets, mixer geometries, valves, test chambers and actuation approaches were investigated.

3.4. Communication network

As preliminary tests at the Hohenschulen experimental farm of Kiel University have shown, the LoRa standard is suitable for communication with soil-embedded sensors. At a depth of 30 - 60 cm, distances of up to 1 km could be covered using a drone as a repeater (Holtorf et al., 2023). In addition to underground-to-aboveground communication (UG2AG) and aboveground-to-underground communication, LoRa as well can be used for underground-to-underground (UG2UG) communication to enable data transfer between sensors (Hardie & Hoyle, 2019). This allows for network architectures with less collection points above ground. In the first project year we carried out additional tests at the Hohenschulen experimental farm regarding the communication network.

4. Economic progress

Within the first project year, the SOILMONITOR has made significant strides in developing a business proposal for pioneering an automated nutrient sensing solution for agriculture. Our strategy aims to solve the specific needs and problems of farmers and agricultural businesses through a unique, user-friendly and cost-effective system. Based on customer surveys and market analysis, a business model has been developed that is in line with the long-term strategy. SOILMONITOR is based on a robust foundation with patents covering innovative technologies related to the sensor. This IP protection ensures our exclusivity in the field.

5. Areas of Impact

The SOILMONITOR project is anticipated to have a range of benefits and impacts on the environment, economy, the agricultural industry, and society at large. It directly addresses the demand for real-time on-site measurement of soil nutrient parameters relevant to agricultural yields, and continuous monitoring of nutrient levels over an entire season.

5.1. Environmental benefits

The potential of SOILMONITOR to reduce nitrate leaching can significantly improve water quality (SDG 6 - Clean Water and Sanitation). This contributes to curbing eutrophication and contamination of groundwater, making water sources safer for consumption, and reducing negative impacts on aquatic ecosystems. The SOILMONITOR can also have a positive impact on biodiversity conservation (SDG 13 - Climate Action), including reducing eutrophication and acidification of water bodies. Since SOILMONITOR is expected to reduce the amount of fertilizer application, it is also expected to reduce nitrous oxide (NOx) emissions, a powerful greenhouse gas.

5.2. Economic benefits

The capability to quantify soil nutrients directly within water extracted from the soil and thus available to growing crops is pertinent to determine proper amounts of fertilization. More accurate and efficient fertilization practices can result in cost savings for farmers by allowing them to apply the right amount of nutrients at the right time, reducing waste and overuse of fertilizers. The SOILMONITOR can thus enhance fertilizer efficiency and improve cost-effectiveness for farmers.

5.3. Impacts on the agricultural Industry

SOILMONITOR advances the growing use of data-driven decision making in agricultural practices. Continuous monitoring over an entire season provides farmers with real-time data to make informed decisions about fertilizer use, planting, and soil management. The project further encourages and facilitates the adoption of sustainable agricultural practices through its aim to provide critical data for nutrient management and crop growth and quality optimization at a low cost and maintenance-free. As a technological innovation, SOILMONITOR has the potential to increase the overall competitiveness and resilience of agriculture and offers the opportunity to set EU and global standards in precision agriculture.

5.4. Societal benefits and impacts

By reducing nitrate levels in food and feed, the project contributes to improved food quality and safety. Reducing harmful levels of nitrate in food helps protect human health by reducing the risk of diseases, such as methemoglobinemia, pregnancy complications, and cancer (Brender, 2020). We therefore expect the SOILMONITOR to have a direct impact on public health and well-being (SDG 3 - Good Health and Well-being).

By providing insight into soil nutrient dynamics, SOILMONITOR aims to help farmers adapt to changing environmental conditions, such as extreme weather phenomena, and market dynamics, such as fluctuations in fertilizer prices or changes in policies and fertilization practices. This way, the project aims to help farmers become more resilient in the face of today's complex and dynamic market environment.

6. Plans for the upcoming year

Activities in the second year of the project will concentrate on combining the different components to realize a prototype system and carry out initial field testing, as well as on the development of the business plan and tech-to-market plan. Once we have considered and secured IP, we will present and demonstrate technological progress in written form and at various events. The SOILMONITOR team will therefore attend several events in the form of fairs, exhibitions, conferences, webinars, and trainings. At these events and beyond, we seek dialogue with interested parties and greatly appreciate requests and conversations.

7. References

Böckmann, S., Titov, I., & Gerken, M. (2021). Extraction of Soil Solution into a Microfluidic Chip. *AgriEngineering, 3*(4), 783-796.

Brender, J.D. (2020). Human health effects of exposure to nitrate, nitrite, and nitrogen dioxide. *Just Enough Nitrogen: Perspectives on How to Get There for Regions with Too Much and Too Little Nitrogen* (pp. 283-294). Cham, Switzerland: Springer.

Chen, M., Schievano, A., Bosco, S., Montero-Castaño, A., Tamburini, G., Pérez-Soba, M., & Makowski, D. (2023). Evidence map of the benefits of enhanced-efficiency fertilisers for the environment, nutrient use efficiency, soil fertility, and crop production. *Environmental Research Letters, 18*(4), 043005.

Federal Ministry of Food and Agriculture (BMEL) (2017b). *Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen* (Düngeverordnung – DüV). http://www.gesetze-im-internet.de/d_v_2017/index.html (accessed 29.10.23).

Hardie, M., & Hoyle, D. (2019). Underground wireless data transmission using 433-MHz LoRa for agriculture. *Sensors*, *19*(19), 4232.

Holtorf, L., Titov, I., Daschner, F., & Gerken, M. (2023). UAV-based Wireless data collection from underground sensor nodes for precision agriculture. *AgriEngineering, 5*(1), 338-354.

Pierce, F. J., & Nowak, P. (1999). Aspects of precision agriculture. *Advances in Agronomy, 67*, 1-85.

Schardt, J., & Gerken, M. (2023). Electrical characterization of optical resonance effects in laterally-nanostructured organic photodetectors. *Optics Express*, *31*(22), 36136-36149.

The Council of the European Communities (1991). EUR-Lex Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. *Official Journal of the European Communities, 375*, 1–8.

Titov, I., Köpke, M., & Gerken, M. (2022a). Monolithic integrated OLED–OPD unit for point-of-need nitrite sensing. *Sensors, 22*(3), 910.

Titov, I., Köpke, M., & Gerken, M. (2022b). Monolithic Integrated OLED–OPD Unit for Point-of-Need Nitrate Sensing. *Proceedings Optical Sensors and Sensing Congress 2022* (AIS, LACSEA, Sensors, ES) OSA - The Optical Society.