OPTIMIZATION OF ELECTROCHEMICAL DEVICE DEVELOPMENT: LASER-INDUCED GRAPHENE ELECTRODE AS AN ALTERNATIVE FOR AGRICULTURAL MONITORING.

Caroline Athaídes Miler[ab], Lucas Minghini Gonçalves[bc], Bruno Vasconcellos Lopes[bc], Betty Braga Gallo[bc], Andrey Borges La Rosa[bc], Diego Alberto Fruchtenicht[bc], Paula Silveira[b], Filipe Felix dos Santos[bc], Neftalí Lenin Villarreal Carrenos[bc], Leandro Machado Carvalho[ab]

[a]Federal University of Santa Maria, Center for Natural and Exact Sciences, Santa Maria, RS, Brazil, 97105-900.

[b]Center for Embedded Devices and Research in Digital Agriculture, SENAI-RS, São Leopoldo, RS, Brazil, 93025-753.

[c]Federal University of Pelotas, Technology Development Center, Pelotas, RS, Brazil, 96010-610.

A paper from the Proceedings of the
17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture
13-15 July 2026
Porto Alegre, Brazil

Abstract.

The agro-industrial sector has actively explored the use of electrochemical devices for in situ field applications. However, the commercial application of flexible sensors faces significant challenges regarding reproducibility and manufacturing errors during large-scale production. This work presents the optimization of the manufacturing process of laser-induced graphene (LIG) electrodes to overcome these limitations, enabling future automation steps in the batch fabrication of three-electrode configuration sensors. To achieve highly reproducible morphological and electrical properties, an extensive test matrix of laser engraving parameters (power, speed, and line density) was evaluated. The optimal configuration was determined via the four-point probe method: 80 mm/s, 14% power (2.8 W), and 100 lines/cm, which resulted in the lowest average electrical resistivity of 0.108 Ω·cm. Subsequently, the three-electrode system (working, counter, and reference electrodes) was assembled using an adhesive mask for contact standardization, controlled thermal curing of silver ink, and modification of the reference electrode with commercial Ag/AgCl ink. The analytical performance of the optimized sensors was evaluated through cyclic voltammetry using a ferri/ferrocyanide redox probe (5 mM $[Fe(CN)_6]^{3-/4-}$ in 0.1 M phosphate buffer). The produced devices exhibited good electrochemical consistency and reproducibility. Statistical analysis among biosensors from the same batch (n = 3) revealed low standard deviations for peak potentials: ±0.0058 V for the oxidation peak and ±0.0185 V for the reduction peak. Moreover, no statistically significant differences were observed in the integration of anodic and cathodic peak heights (paired t-test, p = 0.1430 and 0.1533, respectively). These quantitative results indicate that the proposed metrological approach reduces operational manufacturing flaws. Consequently, the optimized methodology generates stable, responsive LIG electrodes,

The authors are solely responsible for the content of this paper, which is not a refereed publication. Citation of this work should state that it is from the Proceedings of the 17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture: Miler, C. A., Gonçalves, L. M., Lopes, B. V., Gallo, B. B., La Rosa, A. B., Fruchtenicht, D. A., Silveira, P., Santos, F. F., Carrenos, N. L. V., & Carvalho, L. M. (2026). Optimization of Electrochemical Device Development: Laser-Induced Graphene Electrode as an Alternative for Agricultural Monitoring. In Proceedings of the 17th International Conference on Precision Agriculture and 11th Brazilian Congress on Precision and Digital Agriculture (unpaginated, online). Monticello, IL: International Society of Precision Agriculture and Brazilian Congress on Precision and Digital Agriculture.

providing a low-cost platform for portable electrochemical biosensors aimed at continuous monitoring of nutrients, agricultural inputs, and environmental quality in precision agriculture.

Keywords.
Electrode, Electrochemical, Graphene, Fabrication.

Introduction

The agro-industrial sector has actively explored the use of laser-induced graphene (LIG) electrochemical biosensors due to their high sensitivity, rapid response, and low cost (Lopes et al., 2025; Gao et al., 2025; Garland et al., 2018). Electrochemical sensors convert chemical interactions (e.g., oxidation or reduction of analytes) into measurable electrical signals, making them ideal for field monitoring. LIG, in turn, is produced by direct laser irradiation of polymer films (e.g., polyimide), generating a porous graphene structure in a single, solvent-free, maskless step (Garland et al., 2018).

The effective implementation of precision agriculture and smart farming approaches fundamentally depends on the continuous development of such sensor technologies for the in situ monitoring of soil conditions (Yilmaz et al., 2026). However, the practical and commercial application of this emerging generation of flexible devices still faces significant challenges regarding reproducibility and manufacturing errors during large-scale production, factors that compromise analytical reliability and sensor stability (Goldsmith et al., 2019; Behrent, Borggraefe, Baeumner, 2024).

Aiming to overcome these limitations and establish a manufacturing route compatible with batch automation, this work focuses on optimizing the fabrication process of LIG electrodes within a three-electrode system. To achieve this, the ideal laser engraving parameters were selected based on the electrical resistivity of the synthesized material, evaluated via the four-point probe method. This rigorous metrological approach ensures the selection of the most stable configurations, minimizing operational variations and assuring device reproducibility for reliable field monitoring.

Methodology

The fabrication of the three-electrode LIG system began with optimization of engraving parameters: power (2–14%), speed (80–140 mm/s), and line density (100–300 lines/cm). The optimal configuration was selected based on electrical resistivity measured with a Keithley 2400 SourceMeter using the four-point probe method. The ideal parameters were defined as those giving the lowest average resistivity and standard deviation across triplicate measurements.

For assembly, electrical contacts were delimited with an adhesive mask, coated with silver ink, and thermally cured in an oven. The reference electrode was coated with Ag/AgCl ink (BAS Inc., Tokyo, Japan), and the electroactive area was isolated using adhesive tape.

Analytical performance was evaluated by cyclic voltammetry (CV) using an Autolab PGSTAT302N potentiostat in a 5 mM $[Fe(CN)_6]^{3-/4-}$ redox probe (0.1 M phosphate buffer). Scan rates from 20 to 130 mV/s were applied to extract peak currents and calculate the electroactive area of each sample using the Randles-Sevcik equation, validating electron transfer efficiency.

Results

Standardization of LIG was performed using a test matrix combining line densities (100, 200, and 300 lines/cm), laser powers (2 to 14%), and speeds (80 to 140 mm/s). Analyzed in triplicate, the study totaled 189 measurements. The four-point probe method indicated the optimal fabrication condition at 80 mm/s, 14% power (2.8 W), and 100 lines/cm, yielding an average electrical

resistivity of 0.108 Ω·cm.

With these parameters, the three-electrode system (Figure 1) showed consistent voltammetric profiles. Among three biosensors from the same batch, standard deviations for peak potentials were ±0.0058 V (oxidation) and ±0.0185 V (reduction). A paired t-test revealed no statistically significant differences in anodic and cathodic peak heights ($p = 0.1430$ and 0.1533). These results indicate that parameter optimization reduces manufacturing variability, providing devices with stable behavior.

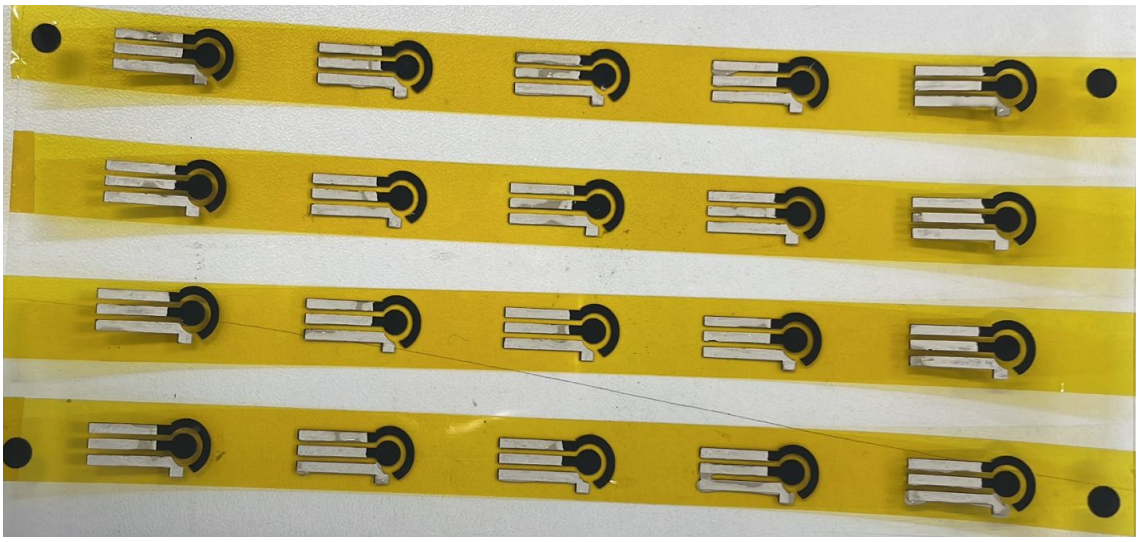

Fig 1. Standardized LIG electrochemical sensors after fabrication and assembly, demonstrating the reproducibility of the proposed manufacturing process.

Such reproducible LIG sensors can be adapted for continuous in situ monitoring via IoT networks (Yilmaz et al., 2026), ranging from direct detection of herbicides such as glyphosate (Lopes et al., 2025) to real-time tracking of soil nutrients, moisture, and pollutants

Conclusion or Summary

Optimization of LIG electrodes using the four-point probe method effectively reduced manufacturing reproducibility issues. The ideal laser condition (80 mm/s, 14% power, 100 lines/cm) minimized electrical resistivity and produced a three-electrode system with stable and consistent voltammetric profiles. Future work will focus on in-field validation of these low-cost, standardized biosensors for continuous monitoring of soil nutrients and environmental pollutants in precision agriculture.

Acknowledgments

This work has been partially funded by the project AgroHealth supported by the Center for Embedded Devices and Research in Digital Agriculture (CEDRA) of SENAI-RS, with financial resources from the PPI IoT/Manufatura 4.0 / PPI HardwareBR of the MCTI, grant number 056/2023, signed with EMBRAPII.

References

Behrent, A.; Borggraefe, V.; Baeumner, A. Laser-induced graphene trending in biosensors: understanding electrode shelf life of this highly porous material. Analytical and Bioanalytical Chemistry, v. 416, p. 2097–2106, 2024.

Garland, N. T. et al. Flexible laser-induced graphene for nitrogen sensing in soil. ACS Applied Materials & Interfaces, v. 10, n. 45, p. 39124-39133, 2018.

Gao, X. et al. Emerging sensor technologies for detecting pollutants in ecosystems. Coordination Chemistry Reviews, v. 542, p. 216849, 2025.

Goldsmith, B. et al. Digital Biosensing by Foundry Fabricated Graphene Sensors. Scientific Reports, v. 9, p. 1-10, 2019.

Lopes, B. et al. Direct-detection of glyphosate in drinking water via a scalable and low-cost laser-induced graphene sensor. Analytical Methods, v. 17, p. 807-815, 2025.

Yilmaz, A. F. et al. Embodied Intelligence for Soil Health toward Sustainable Smart Agriculture: Sensing the Soil with Flexible Geotextiles Sensors. Global Challenges, 2026.