Project

Direct Laser Writing of Chipless RFID Sensors on Bioplastics for Green Monitoring of Food (Dairy) Products

Motivation. In 2025, Ireland's dairy sector processed a record 8.84 billion litres of milk and exported dairy products valued at approximately €7.3 billion to more than 140 international markets, making dairy one of the country's largest agri-food export categories [1]. Despite this success, approximately 31% of Irish households report discarding dairy products weekly, due to spoilage or confusion over date labels, making dairy among the most commonly wasted food categories in Irish homes [2]. This behaviour contributes to the estimated €1.29 billion annual cost of food waste to the Irish economy [3].

Irish and European food systems face increasing challenges in ensuring food quality and safety while reducing environmental impacts and food waste. Current packaging systems rely heavily on fossil-derived plastics, which are predominantly linear in lifecycle, difficult to recycle, and significant contributors to greenhouse gas emissions and environmental pollution [4]. To address tightening safety and sustainability regulations, dairy stakeholders require next-generation, minimal-processing solutions capable of extending shelf life while preserving product quality.

The project will employ low-environmental-footprint direct laser writing techniques combined with bio-based packaging materials to realise **Laser Induced Graphene (LIG) novel chipless RFID sensor tags**, enabling low-cost, fully passive and contactless monitoring of food quality. Three sensing modalities — gas/pH, humidity, and temperature — will be demonstrated in smart packaging use cases for dairy product monitoring (see Figure 1).

Technical Objectives and Approach Chipless RFID sensors will be constructed by LIG electrode materials fabricated on biodegradable plastics using DLW technologies. The shape and surface of the LIG structures will be tailored for each sensing modality: interdigitated electrodes with graphene oxide (GOx) for humidity, lollipop-shaped LIGs with polyaniline (PANI) for pH/NH_3 sensing, and rectangular LIGs for temperature (M1-12). LIG Antenna structures, will resonate in the frequency range 0.86- 2.45 GHz enabling contactless communication over 4-10 com ranges and fabricated on bioplastics using DLW or transferring techniques. Where higher conductivity is required, copper will be substituted with aluminium or zinc. Sensing readout will be achieved via frequency shifts of the antenna upon gas/pH, temperature, or humidity changes (M8-18). Developed sensor and antenna units will be coupled and tested in vitro first and incorporated into dairy packaging for use case demonstration of temperature and spoilage monitoring (M15-24).

The **objectives** of this work are outlined below:

- **O1:** Fabrication: DLW of LIG electrodes and antennas on biopolymers, targeting with sheet resistance < 20 Ω/sq, ≥90% conductivity retention under mechanical deformation and contactless communication over ranges from 4cm - 10m (0.86–2.45 GHz).
- **O2:** RFID sensors: gas sensors detecting 1–100 ppm NH_3 within 1–5 min, humidity sensors responding in < 30s over 10–95%RH, and temperature sensors operating within –5 to +50 °C with response times < 1min.
- **O3:** Use cases: Demonstration of sensor performance in cheese and yogurt packaging, biodegradability testing according to ISO 14855 and EN 13432.

Project Outcomes

1. Fabrication of LIG structures on bioplastics (MS1)
2. Fabrication of sensors on bioplastics and RFID demonstration (MS2)
3. Demonstration of chipless RFID dairy quality monitoring (MS3)

Impact Description. The transition toward circular economy practises is driving the global green packaging market size, valued at $362 billion in 2025 and projected to grow to $ 732 by 2034 [5]. The smart packaging market is also expanding (CAGR of 6.2% from 2024 to 2030) due to the rise of e-commerce and stricter freshness monitoring regulations [6]. The project intersects these markets by developing low-cost, battery-free sensors compatible with sustainable packaging, supporting safer food and circular economy initiatives.

Preliminary data.

The project builds on the expertise of Dr Daniela Iacopino in DLW of LIG sensors on bioplastics for food quality monitoring , including publications demonstrating flexible RFID tags for food thawing events and pH monitoring in packaging [7,8].

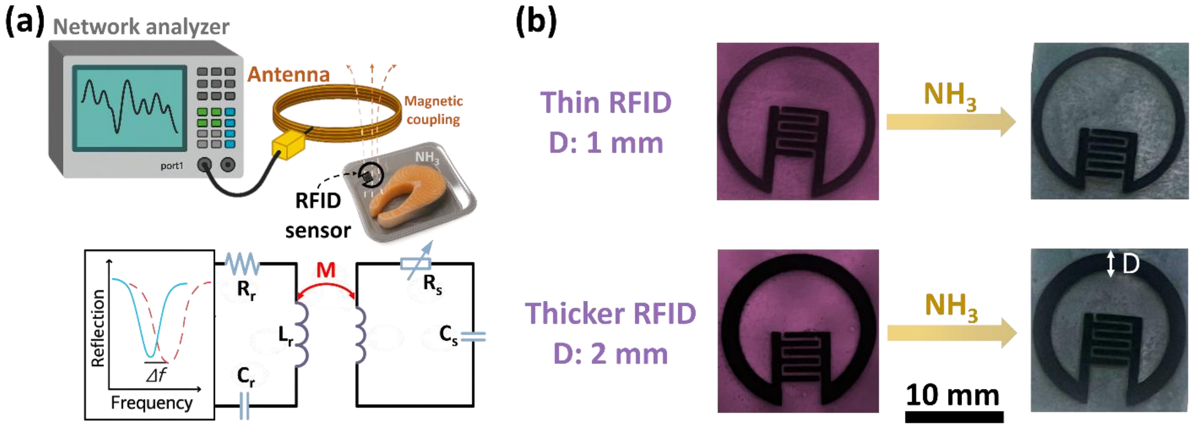

Figure 1. Wireless RFID sensor response to NH3 and self-powered barcode characterization. (a) Schematic of the passive RFID sensing system showing magnetic coupling between an external antenna and the RFID tag, modeled using an equivalent resonant circuit. (b) Digital photographs of thin (D = 1 mm) and thicker (D = 2 mm) RFID tags before and after 30 min of NH3 exposure.

Stakeholder and Industry Relevance. The project supports Enterprise Ireland mission to advance sustainability, innovation, and digitalisation in the Irish dairy sector. The project is also relevant for the Research Ireland Vista Milk centre of excellence of which Dr Iacopino is a Funded Investigator. For stakeholders, including dairy producers, packaging manufacturers, retailers and logistics companies, The project enables real-time, contactless monitoring of product quality, reducing waste and improving consumer confidence. Consumers benefit from enhanced food safety and transparency, while regulatory and environmental stakeholders gain insights into sustainable packaging and supply chain practices. The outcomes from this project are of interest to a number of Irish industries across the dairy value chain. During the project we will engage dairy producers and cooperatives as well as packaging manufactures to co-develop bio-based substrates compatible with laser-induced graphene RFID tags. Dr Iacopino has already started engagement with pomace and brewery companies (Apple Farm and Dingle Distillery) to exploit their waste stream towards production of bioplastics.

Training and Capacity Building. The project will train a postdoctoral fellow in the fabrication of green sensor tags for dairy products. The budget covers a two-year fellowship and travel to three international conferences, providing training in green smart food packaging and professional development opportunities. We target minimum 2 publications in top 10% journals specialising in green materials chemistry and food sustainability, e.g. ACS Sustainable Chemistry & Engineering, ChemSusChem and Food Research International.

References

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Dr Daniela Iacopino

Principal Scientist

Tyndall National Institute

University College Cork | Lee Maltings | Dyke Parade | Cork | Ireland | T12 R5CP

Web: Daniela Iacopino - Tyndall National Institute - Excellence in ICT Research |
Email: **daniela.iacopino@tyndall.ie**