

Towards a Feasible and Robust Technique for Non-invasive Food Analysis

Paulo Quispe¹, and Pedro Bertemes-Filho^{1*}

¹Santa Catarina State University, Dept. Electrical Engineering, Joinville, Brazil

Abstract. Growing requirements for food safety have driven the development of non-invasive monitoring technologies. Among these, electrical bioimpedance (BIA) has emerged as a method for assessing freshness, composition, and adulteration while preserving sample integrity. This work presents a systematic analysis of 259 Scopus-indexed publications from the last 10 years in order to strength and encourage new agricultural applications on food analysis. It was found 21 works on food quality using bioimpedance spectroscopy (BIA), which is the most non-destructive analysis. Due to measurement variability caused by product heterogeneity and environmental factors, standardizing protocols, accurate hardware designs and machine learning (ML) technique are the keys factors towards a feasible BIA system. It was also observed that portability will improve the supply chain management by enabling real-time quality control. It can be concluded that BIA data with ML is a robust and safe tool for the daily basis of consumers, farmers and industry, while supporting industry requirements for sustainable and efficient operations.

1 Introduction

As production and quality demands increase, the agri-food sector is turning to rapid, non-destructive and portable analytical tools to monitor food quality and safety along the whole supply chain [1]. According to the Food and Agriculture Organization of the United Nations [2], globalization and extended supply chains have increased demand for technologies that ensure real-time food quality and safety.

In this context, multiple non-invasive techniques have emerged as viable analytical tools, including ultrasound, capacitive sensing, electromagnetic methods, spectrometry, and colorimetry. Among these, ultrasound methods have proven particularly effective for tracking physicochemical changes in products like ham [3] and potatoes [4], where wave propagation velocity and acoustic impedance correlate directly with moisture loss and structural modifications. Capacitive and dielectric methods have been used for liquid analysis, where parallel-plate and resonator-based sensors with chemometric models detect common milk adulterants [5], while NFC-based systems have demonstrated potential for packaged milk freshness detection [6]. Colorimetric techniques, such as progress-bar strip indicators inside packaging, provide visual freshness information for packaged fish [7].

* Pedro Bertemes-Filho¹: pedro.bertemes@udesc.br

However, these methods face inherent limitations, including temperature dependence [3], the need for frequency-sweep instrumentation and calibration [5], and lighting interference and visual interpretation [7], highlighting the need for robust non-invasive alternatives in food analysis.

Electrical bioimpedance has emerged as a promising technology for non-invasive food analysis. This technique measures resistance (R), which reflects fluid conductivity, and capacitive reactance (Xc), which indicates the capacitive properties of cell membranes [8, 9], enabling real-time monitoring of key parameters like freshness, moisture content, and adulteration [10, 11].

Variability in food properties, as heterogeneity and environmental factors like temperature and humidity complicate measurement standardization and device reliability [12, 13]. Combining bioimpedance measurements with data analysis techniques helps reduce the impact of these limitations and offers a practical substitute for laboratory-based methods [11]. The selection process identified 259 Scopus-indexed publications from 2016-2025 that examined food quality assessment techniques. A bibliometric analysis was conducted on these publications to identify research trends. From this group, 29 papers were selected for detailed review based on their contribution to the field. In this selection process, additional sources were considered beyond Scopus, including master's and doctoral dissertations from institutional repositories. The selected papers focus on key non-invasive methods, including electrical bioimpedance spectroscopy (21 studies in total), ultrasound, capacitive sensing, electromagnetic methods, spectrometry, and colorimetry.

The article aims to explore recent advances in portable bioimpedance devices and other non-invasive food analysis techniques, emphasizing emerging technologies, practical applications, and future opportunities.

2 Bibliometric Analysis

This study employed SciMAT (Science Mapping Analysis Software Tool) for bibliometric analysis to systematically map research trends in non-invasive food quality monitoring. 259 articles were identified in the Scopus database based on a structured query combining keywords related to food quality, non-invasive techniques and sensor technologies, as it follows:

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("food" OR "agri-food" OR "food quality" OR "food safety" OR "food propert*") AND ("non-destructive" OR "non-invasive" OR "contactless") AND ("sensor*" OR "transducer*" OR "biosensor*" OR "impedance" OR "bioimpedance" OR "spectroscop*" OR "optical sensor*" OR "ultrasound" OR "acoustic") AND ("dielectric propert*" OR "conductivity" OR "capacitance") AND PUBYEAR > 2015 AND PUBYEAR < 2026 AND (LIMIT-TO(SUBJAREA, "AGRI")) AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "re")) AND (LIMIT-TO(EXACTKEYWORD, "Quality Control") OR LIMIT-TO(EXACTKEYWORD, "Food Safety") OR LIMIT-TO(EXACTKEYWORD, "Food Quality") OR LIMIT-TO(EXACTKEYWORD, "Food Analysis") OR LIMIT-TO(EXACTKEYWORD, "Food Storage") OR LIMIT-TO(EXACTKEYWORD, "Food Products") OR LIMIT-TO(EXACTKEYWORD, "Food"))
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These publications from 2016 and 2025 represent the major developments in the domain of non-invasive food analysis. From this dataset, emerging trends, keyword clusters, and author networks were visualized using SciMAT.

The strategic diagram Fig.1 reveals key research clusters in non-invasive food monitoring, with "food-quality", "bioimpedance-spectroscopy" and "machine-learning" emerging as dominant motor themes (high centrality and density). These established areas demonstrate strong interdisciplinary connections, validating current research priorities.

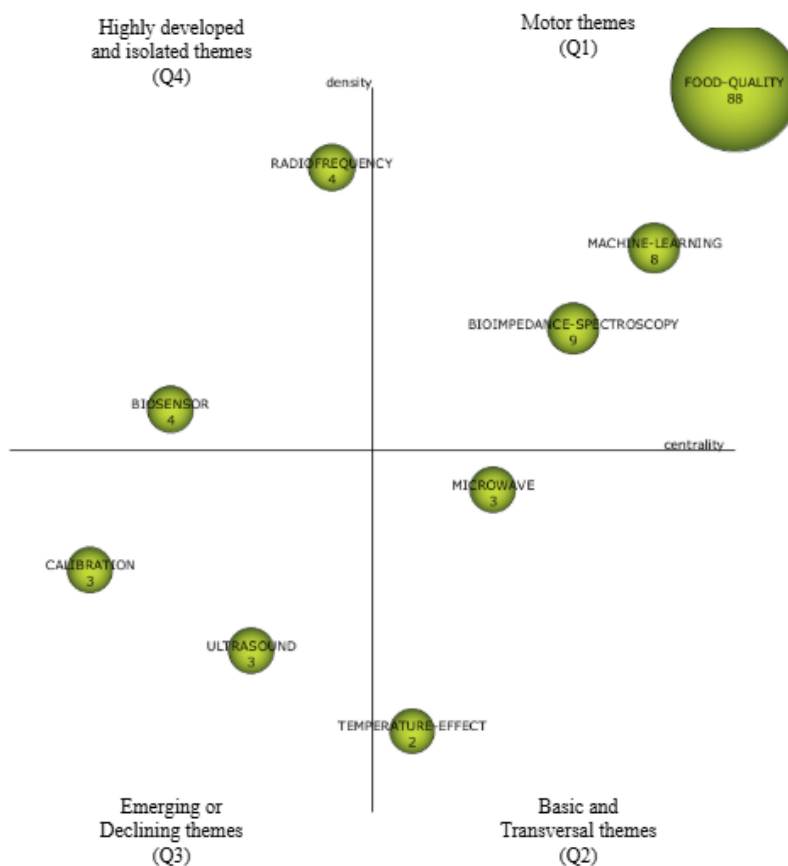


Fig. 1. Strategic diagram of bibliometrics about food analysis from 2016 to 2025. Quadrant 1: motor themes. Quadrant 2: basic and transversal themes. Quadrant 3: emerging or declining themes. Quadrant 4: highly developed and isolated themes.

The thematic network Fig.2 provides a detailed visualization of the intellectual structure and interconnections among key research themes in non-invasive food quality monitoring. At its core, the network highlights "bioimpedance" as a foundational concept, closely connected to wider concepts such as "non-destructive-analysis" and "food-quality". However, the analysis reveals a notable gap in the integration of "Artificial-Intelligence" with core bioimpedance methodologies, as evidenced by weak or peripheral connections between these domains. Bridging this gap could lead to major advancements by enabling the creation of smarter, adaptive systems that support real-time monitoring and decision-making.

These findings highlight three key strategic priorities: Develop clearer guidelines, models, or principles that explain how Artificial Intelligence can process and interpret data obtained from bioimpedance spectroscopy measurements, address environmental interference to enhance the performance of portable devices, and advancing sensor fusion to incorporate other non-invasive technologies for food evaluation. Together, these insights provide a clear direction for future research, emphasizing the need to combine bioimpedance spectroscopy

precision with advanced technological approaches to enhance real-time food monitoring systems.

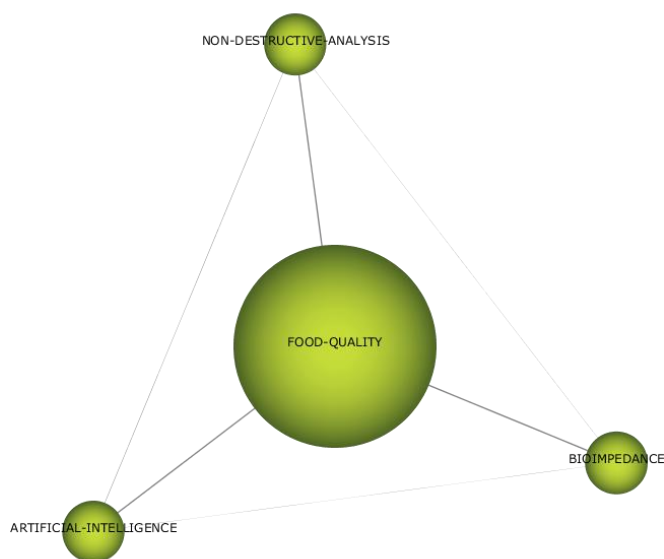


Fig. 2. Thematic network structure of the cluster “FOOD-QUALITY”.

3 Basic non-Invasive methods for Food Analysis

Recent advancements in non-invasive food analysis methods (Table 1) have transformed quality monitoring by allowing the evaluation of both structure and composition without damaging the sample, making them suitable for real-time supply chain applications. Among these technologies, ultrasound-based methods have demonstrated exceptional capability for monitoring physicochemical changes in different kinds of food. Studies on cured ham [3], potatoes [4], and edible oils [14] have established reliable correlations between acoustic parameters (propagation velocity, attenuation, and impedance) and critical quality indicators including moisture content, density, and viscosity. While these ultrasonic techniques show promise, their accuracy can be compromised by material anisotropy and temperature variations [4], with additional limitations observed in dehydrated products due to signal attenuation.

Complementary to ultrasonic approaches, capacitive measurement methods have emerged as cost-effective solutions for liquid food analysis. Research on milk quality assessment has demonstrated the effectiveness of parallel-plate and cylindrical capacitor configurations for product differentiation [5, 6]. However, the precision of these techniques is still limited by their sensitivity and vulnerability to environmental factors.

Similarly, colorimetric sensing platforms, such as progress-bar strip indicators for fish packaging [7], provide quick visual freshness checks based on volatile amine accumulation and can be easily interpreted by non-specialists. However, their performance still depends on controlled lighting conditions and standardized color reading, and they remain slower and less precise than fully quantitative analytical methods.

Table 1. Overview of non-invasive methods in quality control of different types of food

Technique	Food	Results	Limitations
Ultrasound	Ham	Correlation established between ultrasound velocity (1 MHz) and salt/oil concentration variations during curing [3, 16].	Meat anisotropy effects.
Ultrasound	Potato	Air-coupled ultrasound (250 kHz) monitored drying processes, correlating acoustic parameters with moisture, density, and texture [4].	High attenuation in dehydrated products.
Ultrasound	Edible oil	Ultrasound inspection (2.25 MHz) discriminated against pure and adulterated oils by correlating velocity, attenuation, and frequency components with viscosity/density [14]	Temperature dependence
Capacitive	Milk	Parallel-plate and resonator sensors with chemometric models detected common milk adulterants [5].	Requires frequency-sweep RF equipment
Capacitive	Milk	NFC capacitive tags detected packaged milk freshness via smartphone capacitance measurements [6]	Low sensitivity
Colorimetric	Fish	Progress-bar colorimetric strip indicated packaged fish freshness via volatile amines [7].	Slow response
Electromagnetic	Sugar	Broadband electromagnetic sensors detected contaminants and packaging defects using microwaves/THz waves [17].	High cost
Spectrometry	Bread	Hyperspectral infrared analysis predicted fat/moisture content in bakery products [15]	High cost, complex calibration

Spectroscopic techniques, particularly hyperspectral infrared analysis [15], have shown remarkable potential for non-destructive measurement of compositional parameters like fat and moisture content in baked goods. However, the adoption of these systems remains limited due to high equipment costs and the need for complex calibration procedures.

Among all non-invasive methods, electrical bioimpedance has distinguished itself as a particularly versatile analytical tool [9]. Bioimpedance measures a biological material's opposition to alternating current (AC), quantifying its resistance and capacitive properties, which are directly influenced by cellular structure, fluid content, and chemical composition [8]. This non-destructive method is revolutionizing food quality analysis by enabling real-time assessment of ripeness, freshness, and adulteration across diverse products, from fruits to meats and beverages [1], as further detailed in Figure 3.

4 Bioimpedance Applications in Food Analysis

The versatility of electrical bioimpedance for food quality assessment has been demonstrated across a wide range of products, with particularly notable applications in agricultural products, meat, and liquid food analysis (Figure 3). For agricultural products, bioimpedance has enabled precise detection of internal defects and quality parameters. Studies using specific frequency impedance spectroscopy have successfully predicted internal browning in apples [18]. Similar approaches have proven effective for monitoring moisture dynamics during dehydration processes [19] and assessed seed vigour in rice by correlating impedance parameters with bound-water content and microstructural changes [20]. Advanced implementations combining impedance spectroscopy with equivalent circuit modelling have

shown strong performance in detecting freeze damage in citrus fruits [21] and blueberries [22]. The technique's versatility extends to diverse agricultural applications, from non-invasive freezing injury assessment in potatoes [23] to dry matter content prediction and varietal classification using machine learning-enhanced systems [24]. Optimized electrode configurations have further expanded applications, achieving reliable maturity detection in tomatoes [25] and bruise identification for quality control [26].

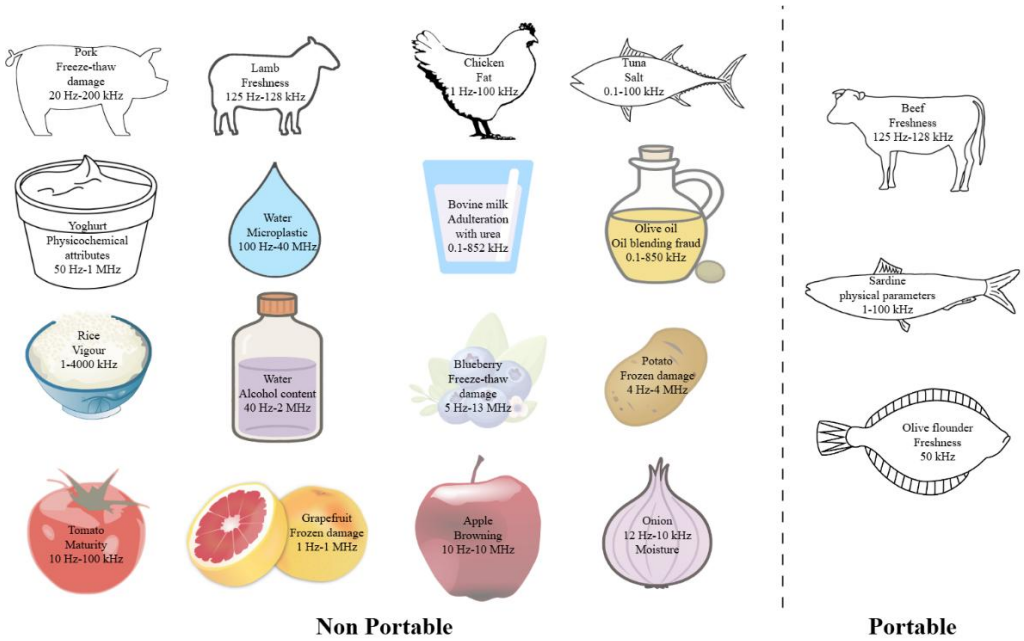


Fig. 3. Classification of bioimpedance applications in food quality control by product category, key metric, spectroscopy frequency range and system portability.

In meat and seafood products, bioimpedance has emerged as a reliable tool for non-destructive quality evaluation across multiple species. The integration of impedance spectroscopy with image classification techniques has significantly improved predictive accuracy for meat freshness [10]. This method is also effective for processed meat. Recent applications include assessing freeze-thaw cycles in pork using Cole impedance modelling [27], evaluating mutton tenderness through ensemble learning algorithms [28], and measuring body fat composition in live chickens using specialized electrode configurations [29]. In seafood applications, bioimpedance has been used to estimate salt content in canned tuna [30]. Correlations between bioimpedance spectrum and morphological parameters in sardines have been established, offering non-lethal monitoring solutions [31]. The method also shows strong correlation with organoleptic quality indicators in fish [32], demonstrating its versatility across diverse animal protein applications.

Liquid food analysis represents another important application domain, where bioimpedance has proven valuable for both composition monitoring and adulteration detection. Studies have successfully employed the method for alcohol content determination in distilled water [33] and for identifying olive oil blending fraud [12], showcasing its sensitivity to compositional changes in high-value liquid products. In dairy applications, the method has demonstrated effectiveness in characterizing yogurt varieties through impedance profiling [34] and detecting urea adulteration in raw milk with high accuracy [11]. This method is also effective for environmental monitoring, particularly in detecting microplastic contamination

in water sources [35]. These diverse applications benefit from the method's ability to detect subtle changes in electrical properties while requiring minimal sample preparation

5 Challenges and Future Opportunities

Despite significant advances in portable bioimpedance devices and other non-invasive techniques, several challenges must be addressed before this tool can be fully implemented in the food industry. A primary challenge is the inherent variability in the physical and chemical properties of foods, such as compositional heterogeneity in agricultural products, meats, and liquid products [11, 12]. This variability makes it difficult to standardize measurements, which can affect accuracy and repeatability.

Environmental factors, including temperature, humidity and contaminants, affect the bioimpedance measurements [13, 25]. For instance, temperature fluctuations significantly alter impedance readings in bovine milk [11] and edible oils [4], while freeze-thaw cycles affect the electrical properties of meat and produce [22, 27]. To address these points, future devices should include real-time compensation systems that adjust for external conditions.

Improving sensitivity and resolution remains another critical hurdle. While capacitive techniques have demonstrated utility in milk freshness assessment [6], their limited precision restricts high-resolution applications. New approaches use machine learning to improve how data is understood, as seen in tomato bruise detection [26] and mutton tenderness classification [28]. Integrating ML analytics with multi-frequency bioimpedance systems could help overcome these limitations [13, 23].

In addition, the integration of IoT-enabled digital platforms and wireless connectivity will facilitate real-time monitoring across supply chains. These innovations, coupled with ML techniques, could revolutionize food safety by enabling rapid, data-driven interventions.

6 Discussions and Conclusion

Non-invasive techniques, particularly electrical bioimpedance, provide a reliable tool for evaluating a wide range of food products, including fruits, vegetables, meats and liquids by offering fast and non-destructive alternatives to traditional laboratory methods. The ability of these technologies to assess critical parameters like freshness, moisture content, and adulteration in real time has created new possibilities for food quality monitoring throughout supply chains.

However, reaching its full potential requires addressing key challenges including food property variability, external factor influences, and the need for improved measurement sensitivity and precision.

The future of these technologies is promising, with significant advances in hardware, software, and data analysis techniques. The integration of Artificial Intelligence (AI) and machine learning is improving bioimpedance-based prediction and classification capabilities, while the miniaturization and cost reduction of specialized integrated circuits are enabling more accessible and efficient portable devices. Furthermore, combining bioimpedance with other non-invasive techniques like infrared spectroscopy and electromagnetic sensors offers unprecedented potential for comprehensive food quality monitoring systems.

In conclusion, recent advances in portable bioimpedance devices and other non-invasive technologies have the potential to transform the food industry. By providing more efficient and precise methods for food quality monitoring, these technologies can not only ensure food safety but also optimize production and distribution processes to meet growing global demands for high-quality food.

The authors declare no conflict of interest.

Paulo Roberto Quispe Cardenas worked on conceptualization and methodology and wrote the first draft of the manuscript. Pedro Bertemes-Filho supervised the study, reviewed and edited the final manuscript, and analyzed the results. All authors approved the final version.

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