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RESEARCH

Non-invasive Analyses of Packaged Food Using Time-Domain NMR Relaxometry

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Abstract
This overview explores time-domain nuclear magnetic resonance (TD-NMR) relaxometry as a rapid, non-invasive analytical tool for evaluating packaged food products. While traditional invasive methods are often laborious and time-consuming, TD-NMR harnesses the radio-frequency transparency of most packaging materials to enable direct analysis. Furthermore, by utilizing relaxometry and diffusion measurements, this technique provides critical data on fat and water content, compartmentalization, texture, spoilage, and adulteration. In particular, this work outlines the fundamental principles of TD-NMR and highlights its application in dairy, edible oils, sauces, jams, and beverages. Ultimately, as this technology matures for consumer use, TD-NMR stands to significantly enhance food safety, quality, and supply chain transparency by facilitating straightforward, on-site analysis of packaged goods.

Keywords TD-NMR · Relaxometry · Diffusion · Packaged food · Non-invasive analysis

Introduction

Concern for food safety is likely as ancient as human history itself. Our modern understanding of the field is the culmination of centuries of discoveries, inventions, and regulatory milestones rooted in the earliest stages of civilization (Maestro et al. 2022). In the contemporary era, however, the landscape of food quality control has evolved significantly due to the globalization of supply chains and increasing matrix complexity. Consequently, modern regulatory policies, such as the *Hazard Analysis and Critical Control Points* (HACCP) (Motarjemi and Warren 2023) system and *Codex Alimentarius guidelines* (Lee et al. 2021), have become central to food safety governance. To adhere to these mandates, there is a critical need for rapid, accurate, and ideally non-invasive analytical technologies. By enabling the monitoring of quality parameters with minimal disruption to production workflows, such technologies ensure both safety and efficiency in the global food supply.

In this context, electromagnetic (EM) wave–based techniques represent a robust and non-invasive class of analytical tools for assessing food products. These methods harness the interaction of EM radiation, ranging from high-energy gamma rays to low-energy radiofrequencies (RF), to nondestructively probe the internal composition of food products and their packaging (Zhang et al. 2024). The interaction between EM waves and food matrices is dictated by essential electromagnetic parameters, including dielectric permittivity, conductivity, and magnetic susceptibility (Nelson 2008). These parameters govern the extent to which EM energy is absorbed, reflected, or transmitted through the food product and its packaging, providing crucial information into their intrinsic properties.

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For non-invasive analysis of packaged food products, a fundamental requirement is the relative transparency of the packaging material to incident electromagnetic radiation. This enables EM waves, such as microwaves, terahertz waves, and near-infrared light, to penetrate the packaging for tasks like detecting contaminants, assessing quality, and monitoring changes within the food (Wu et al. 2022; Zhang et al. 2024). Conversely, high-energy modalities, such as X-rays and gamma rays, are well-suited for penetrating a wide range of packaging materials due to their inherent penetrating power, as noted by Sadler et al. (2001) and Ben Akacha et al. (2025). Nevertheless, their interactions with the food matrices themselves are often limited. This is because these forms of radiation primarily interact with high-atomic-number elements through mechanisms like the photoelectric effect and Compton scattering (Sadler et al. 2001). Consequently, while effective for detecting foreign objects such as metal contaminants, their utility in assessing subtle changes in chemical composition or intrinsic food quality is constrained. Furthermore, the ionizing nature of these radiations necessitates stringent safety protocols for both operators and consumers, especially when considering large-scale applications (Ben Akacha et al. 2025).

In contrast, lower-energy radiation within the visible ranges facilitates visual and spectroscopic inspection of foods when packaged in optically transparent materials like glass or certain polymers (Rodriguez-Saona and Allendorf 2011; Beć et al. 2022). However, most commercial packaging is opaque to infrared and microwave radiation due to high absorption or scattering, making these modalities less effective for through-package analysis (Aboud et al. 2019; Zeng et al. 2022). Radiofrequency (RF) radiation, occupying the lowest energy portion of the EM spectrum, exhibits superior transmission characteristics through common non-metallic packaging materials, including plastic and glass. While penetration through thick metallic layers is generally poor, very low RF frequencies (typically below 2 MHz) can effectively traverse thin metallic foils or multilayered laminates, enabling studies of food matrices within such containers (Jiao et al. 2018; Ma et al. 2022; Gomes et al. 2023). These unique penetration properties position RF-based techniques as particularly well-suited for the non-destructive inspection of a diverse array of packaged food products.

Among the most powerful RF-based techniques is nuclear magnetic resonance (NMR), which exploits the magnetic properties of atomic nuclei in conjunction with RF excitation to derive structural and dynamic information about molecules within the food matrix. NMR phenomena are governed by the Zeeman effect, wherein nuclear spin states are split in the presence of an external static magnetic field ($\mathbf{B}_0$), enabling resonance absorption at specific frequencies determined by the Larmor relationship in Hertz (Eq. 1) (Levitt 2008; Claridge 2016a):

$$\nu = \frac{-\gamma B_0}{2\pi} \tag{1}$$

where ν is the resonance frequency and γ is the gyromagnetic ratio of the nucleus.

Additionally, magnetic field strength ($\mathbf{B}_0$) is a fundamental factor in NMR, directly influencing both spectral resolution and the signal-to-noise ratio (SNR). As $\mathbf{B}_0$ increases, spectral resolution improves approximately proportionally, allowing for a clearer separation of different chemical signals (Boyd et al. 1994; Li and Xiang 2025). Furthermore, SNR is not only related to the magnetic field but is also directly proportional to $\mathbf{B}_0$ raised to the power of three-halves ($\mathbf{B}_0^{3/2}$) (Hoult and Richards 1976). Consequently, higher magnetic fields result in a significantly stronger signal, which is critical for obtaining high-quality spectra, particularly in applications with limited sample sizes or low concentrations.

Therefore, standard high-resolution NMR instruments rely on strong, homogeneous magnetic fields generated by superconducting magnets, with approximately 50-mm bore and cooled by liquid helium (Claridge 2016b). More recently, middle-resolution, benchtop NMR spectrometers, based on permanent magnets, have been introduced. The magnetic strength in these instruments normally ranges from 1 to 2.5 T, but they have very small bores or gaps that fit only 5-mm samples (Eccles 2010; Mitchell et al. 2014; Singh and Blümich 2016). The analyses using the NMR spectrometers are based on several spectral features like chemical shift and spin-spin coupling among several other parameters.

High-resolution and medium-field NMR has emerged as a powerful, non-destructive tool in food analysis, offering detailed insights into molecular composition without requiring extensive sample preparation. As reviewed by Solovyev et al. (2021), such applications underscore the broader potential of high-resolution NMR in food quality control, authenticity verification, and metabolic profiling. The ability to obtain comprehensive chemical fingerprints makes it particularly valuable for detecting adulteration, monitoring fermentation, and assessing compositional differences linked to geographical origin or agricultural practices.

Despite these capabilities, such applications have largely remained within specialized or research-focused domains. High-resolution NMR has been successfully employed to authenticate the geographical origin of olive oils by detecting subtle differences in the composition of triacylglycerols and minor components, thereby supporting efforts to combat food fraud (Vigli et al. 2003). Additionally, Musio et al. (2024) demonstrated that NMR techniques are highly suitable and robust for routine food control, even when samples are prepared and analyzed across different laboratories with varying equipment and operators. Specifically, a classification model built using 1D ^{1}H NOESY spectra from two independent laboratories achieved a 97.62% correct classification rate for assessing the geographical origin of tomato samples, demonstrating the strong applicability of NMR data for discriminating between samples from different regions and highlighting the comparability of NMR data across diverse laboratory settings for food authenticity and traceability.

Moreover, Haddad et al. (2022) successfully classified cheese samples based on the producing species, geographical origin, variety, and producer. It also highlighted that variables related to the position or distribution of fatty acids in triacylglycerols were crucial biomarkers for these classifications, indicating a significant influence of the rumen microbiota. Furthermore, Kandasamy et al. (2024) proposed that high-resolution magic angle spinning (HRMAS)-NMR-based metabolomics is an effective method for discriminating between the metabolomic profiles of yogurt made from cow milk and goat milk. This distinction provides valuable preliminary information that could be useful for authenticity verification and detecting adulteration in yogurt products.

However, despite its clear advantages, the widespread industrial adoption of high-resolution NMR in food science remains limited. This powerful, non-destructive analytical tool, with its proven ability across diverse applications, faces significant hurdles. These include the high cost of instrumentation, the necessity for specialized expertise, and the prevalence of alternative methods that are often perceived as more cost-effective or readily available. Another significant challenge would be tracking the potential migration of chemical substances, such as antioxidants, antimicrobial agents, and plasticizers, from active packaging materials into the food matrix during contact. Such migration poses potential health risks, particularly for vulnerable populations, and can alter the sensory and nutritional attributes of the food (Zhang et al. 2025).

A few examples of a high-resolution NMR superconducting spectrometer and magnetic resonance imaging (MRI) applications, in packaged food, are described in Table 1. Examples mentioned focus on analysis performed without opening the packages for sampling.

It is important to note that these high-resolution measurements were conducted using a wide-bore spectrometer. Initial studies focused on quantifying acetic acid in aged bottled wines, demonstrating the exceptional selectivity of high-resolution NMR. However, due to the probe requirements to fit an entire wine bottle, manual shimming on room temperature was a limitation, leading to broad peaks and errors in quantitative measurements. Therefore, the latter explored an optimization of pulse acquisition parameters. By using the 1331 water suppression pulse sequence, it was possible to obtain an optimal value for both narrowing the water signal on wine samples at minimal duration. This approach proved to address the room temperature shimming problems mentioned before. Nevertheless, these instruments also based on wide-bore superconducting magnets have been rarely used in food science, due to the high cost (Capitani et al. 2017).

Another class of NMR instruments that have huge potential to obtain very important information about food quality, like water and fat spatial compartmentalization, is MRI tomographs (Table 1). Figure 1 shows the photo of a packed bologna with dimensions (a) and the respective magnetic resonance imaging (b). The image was obtained in Varian Instruments, based on a 2.01 T Oxford horizontal superconducting magnet with a 310-mm bore. The image, obtained with a T_1-weighted pulse sequence, shows the size and distribution of the fat cubes (white spots) in the bologna. One possible application for acquiring this

Table 1 Papers reporting non-invasive analysis on high-resolution NMR and MRI on packaged food products

	Packaged food	Objective	Measurement	Reference
High-resolution NMR	Wine	Perform a non-invasive and non-destructive investigation on wine acetification	^{1}H pulse acquisition	Gorman (2002); Weekley et al. (2002)
		Determine the degree of wine spoilage	^{1}H and ^{13}C pulse acquisition	Weekley et al. (2003)
		Optimize phase alternated water suppression pulse sequence towards a rapid throughput quantitation of the oxidation level of full wine bottles	1331 water suppression pulse sequence	Sobieski et al. (2006)
MRI	Milk and milk whey	Determine casein concentration on sealed dairy products by spin-spin relaxation measurements	CPMG and fastSE	Alekseev and Khripov (2015)
	Semi-hard cheese	Develop a non-invasive 3D MRI method to monitor individual eye growth in semi-hard cheeses during ripening	3D fast spin echo	Musse et al. (2014)

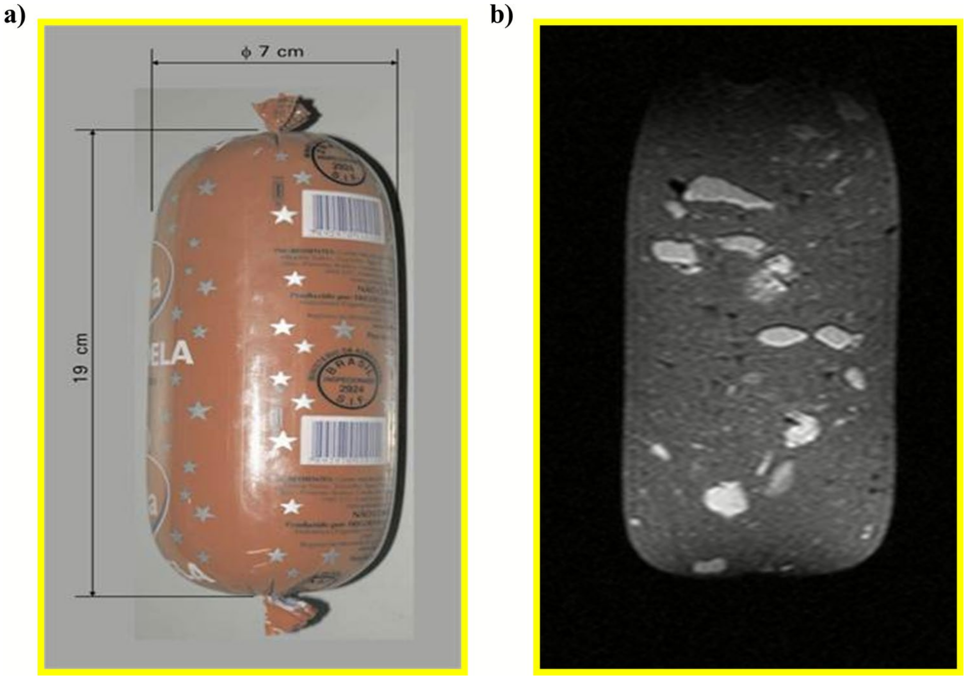

Fig. 1 Packaged bologna picture with sample dimensions (**a**) and respective magnetic resonance imaging (**b**). The white spots correspond to the fat cubes of the packaged bologna. Image obtained with a T_1-weighted sequence in Varian Instruments, based on a 2.01 T Oxford, 310-mm bore

type of image for bologna samples would be calculating the fat cubes to track fat content or adulteration.

Lower cost and less common MRI instruments, based on resistive electromagnets and permanent magnets, are also rarely used in food science. Alekseev and Khripov investigated casein content in milk products. The authors correlated the water protons spin-spin relaxation time with the number of hydrogen atoms bound to casein micelles through chemical exchange and hydration processes in their measurements. Both imaging NMR and T_2 values were evaluated through CPMG and fastSE pulse sequences, acquired in a medical NMR imaging unit Vectra – General Electrics Medical Systems (Fairfield, Connecticut, the USA), resonance frequency for ^{1}H of 21.6 MHz. Their findings stated that the values of milk and milk whey T_2 depended on the manufacturer's geographical location, fraction of total mass of solids in the skimmed milk, changes in temperature, and pH. They also conducted a quantitative analysis of their samples and determined a limit of quantification of 0.5% for casein within their methodology (Alekseev and Khripov 2015). In the meantime, Musse and coworkers developed a non-invasive 3D MRI method to monitor individual eye growth in semi-hard cheeses during ripening. These types of dairy products are characterized by their eyes in terms of number, size, and shape. Classic evaluation methods to assess these characteristics are destructive and most of the time non-reproducible. Therefore, MRI as a non-invasive imaging method is an alternative as a quality control procedure. The study optimized MRI parameters by comparing eye volume estimations with computed tomography measurements. They used a 1.5 T MRI (Magnetom Avanto, Siemens) device and 3D fast spin echo pulse sequence in the measurements. For image processing, the authors trained a model to estimate eye volume on artificial cheese and then applied it to the samples. Collected data indicated that MRI images were not affected by any susceptibility artifacts that may have occurred during image acquisition. Besides, spatial resolution demonstrated high accuracy for eye volume estimation, showing results similar to the computed tomography measurements. Moreover, the image processing algorithm allowed means of observing and following eye formation in the samples (Musse et al. 2014). Furthermore, MRI options for food industrial applications still rely on machine learning algorithms for image processing; however, the approaches presented demonstrate a huge potential for dairy adulteration detection.

In contrast to high-resolution NMR and MRI, time-domain NMR (TD-NMR) represents a practical alternative for non-invasive food quality analysis (Colnago et al. 2011; Resende et al. 2021; Moraes and Colnago 2022; Osheter et al. 2022). The TD-NMR has been used in food science for more than half a century (Todt et al. 2006; van Duynhoven et al. 2010). TD-NMR, based on permanent magnets, operates under low (<0.7 T) and often inhomogeneous ($\Delta\mathbf{B}_0 > 10$ ppm). As the linewidth of the signals is much larger than the chemical shift dispersion, all liquid samples give a single broad signal. Therefore, the NMR signals are processed in the time domain and these instruments are known as time-domain NMR (TD-NMR), low-field NMR (LF-NMR), or low-resolution NMR (LR-NMR). The early application of TD-NMR in food science was performed in dedicated instruments for industrial quality control. These analyses are performed using the intensity of free induction decay or spin echo signals, in one or two positions, and are used in the quantitative analysis of water, fat content, and solid fat content among other applications (Todt et al. 2006). Additionally, early TD-NMR instruments provided diffusion measurements for assessing droplet size in emulsions (Goudappel et al. 2001).

In the last three decades, these instruments have become more versatile and many other food applications have been developed. Specifically, TD-NMR relaxometry (which also includes low-frequency MRI) (Ezeanaka et al. 2019), based on spin-lattice (T_1) and spin-spin (T_2) relaxation times, becomes widespread. The relaxation measurements are sensitive to molecular dynamics and local environmental interactions given important information about food quality (Colnago et al. 2011; Osheter et al. 2022). These relaxation parameters provide indirect but highly informative proxies for food properties such as water content, fat distribution, texture, solid-to-liquid phase ratios, and protein denaturation, all of which are critical indicators of spoilage, adulteration, or thermal processing (Haiduc and van Duynhoven 2005; Trezza et al. 2006; Nikolaeva et al. 2020). TD-NMR systems are increasingly deployed in both industrial, academic, and regulatory laboratories for the routine assessment of moisture in meats, ripeness in cheeses, and fat content in dairy products, in the same cases, even without the need for sample removal from packaging (Fig. 1) (Moraes and Colnago 2022).

Finally, diffusion measurements, when coupled with TD-NMR spectrometers, offer a powerful and accessible tool for characterizing various food matrices (Osheter et al. 2022; Uguz et al. 2022; Fakhar et al. 2024). In this context, diffusion measurements have been successfully used for the study of the distinct mobility of water molecules within different microenvironments, consequently providing valuable insights into product microstructure, water binding, and textural properties (Osheter et al. 2022). For instance, diffusion coefficients can differentiate between free and bound water, which in turn reveals information about gelation (Colsenet et al. 2005), emulsification (Pedersen et al. 2003), and hydration states (Métais and Mariette 2003) in products like dairy (Song 2009; Kharbanda et al. 2023), meat (Laghi et al. 2017), and baked goods (Hopkins et al. 2019). Moreover, this non-invasive approach allows for the assessment of food quality, freshness, and even the detection of adulteration, all without the need for extensive sample preparation. Furthermore, the simplicity and portability of low-field NMR, coupled with the specificity of its relaxation and diffusion measurements, are paving the way for rapid and effective analysis directly within food production and processing environments. This combination offers a unique solution for on-site quality control and real-time monitoring for food matrices.

NMR Relaxation and Diffusion in Food Matrices

Nuclear magnetic resonance (NMR) spectroscopy is increasingly recognized as an essential analytical tool for probing the structure, dynamics, and quality of complex food matrices. Central to this capability in TD-NMR are spin relaxation and molecular diffusion measurements, which offer deep insights into molecular mobility, compartmentalization, and phase interactions. The two relaxation processes are known as longitudinal, spin lattice or T_1 and transverse, spin-spin or T_2 relaxation times. T_1 is the time constant of the recovery of the magnetization vector along the *z*-axis or the time constant of the return of the magnetization to thermal equilibrium, while T_2 is the time constant that describes the decay of transverse magnetization (spin-spin relaxation), a result of dephasing among neighboring spins (Levitt 2008). T_1 and T_2 are strongly dependent on molecular dynamics and are remarkably sensitive to changes in food moisture and fat distributions, textural properties, and the physicochemical environment (Moraes and Colnago 2022).

This variability is due to differences in how the molecules move and the constraints placed upon them by their environment (compartmentalization). T_1 and T_2 are similar for solution but they might have different relaxation times in heterogeneous and viscous samples. For instance, T_2 of water and fat in meats is very close but $T_1 \gg T_2$ making it suitable for water/fat quantification (Moraes et al. 2016). The water that is bound to protein or polysaccharide structures has restricted dynamics and consequently a shorter T_2. On the other hand, T_1 is longer for the same molecular dynamic restriction as observed in meat. In contrast, free water in less constrained areas of the food system relaxes more slowly, exhibiting a longer T_1 and T_2. These distinct differences in relaxation behavior can be precisely measured using specific magnetic resonance pulse sequences designed to target each relaxation mechanism (Moraes and Colnago 2022).

Inversion recovery pulse sequence is a standard sequence to measure T_1. It consists of a 180° inversion pulse followed by a variable delay time τ, and then a 90° detection pulse. The longitudinal magnetization $M_z(\tau)$ follows an exponential recovery (Eq. 2):

$$M_z(\tau) = M_0(1 - 2e^{\frac{-\tau}{T_1}}) \quad (2)$$

This approach is well-suited for distinguishing lipid-rich phases from aqueous compartments in food products such as cheese, meat, or emulsions (Curti and Anedda 2023; Xu et al. 2024). Several other fast pulse sequences to measure T_1 have been used in food analysis (Monaretto et al. 2015; Moraes et al. 2016).

Carr-Purcell-Meiboom-Gill (CPMG) is a standard pulse sequence to measure T_2. The sequence begins with a 90°

pulse followed by a time interval tau (τ), a series of 180° refocusing pulses, with a 90° phase shift from the initial pulse producing a spin echo after every time (τ) from the 180° train of pulses. The intensity of the echoes signal decays exponentially as a function of time (Eq. 3) (Claridge 2016a):

$$M_{xy}(\tau) = M_0 e^{\frac{-\tau}{T_2}} \tag{3}$$

Within the food samples context, these matrices typically exhibit multi-exponential T_2 decays due to the coexistence of multiple water and fat environments. These are resolved by either fitting to a sum of exponentials or using inverse Laplace transform (ILT) methods (Ioannidis et al. 2020), which provide a continuous distribution of relaxation times (Eq. 4):

$$M(\tau) = \sum_{i=1}^{N} A_i e^{\frac{-t}{T_{2i}}} \tag{4}$$

where N corresponds to the number of exponential decays; A_i denotes the relative amplitude of each component, associated with proton populations in distinct physical states. For example, in a piece of fruit, one might observe short T_2 values from intracellular water tightly associated with membranes, and long T_2 components from vacuolar or intercellular free water (Marigheto et al. 2008; Ribeiro et al. 2010).

In addition to relaxation, NMR offers unique access to molecular diffusion, a parameter deeply tied to structural organization and phase boundaries. The self-diffusion coefficient D quantifies the random motion of molecules and is typically measured using pulsed-field gradient (PFG) techniques. The signal attenuation due to diffusion is described by the Stejskal-Tanner equation (Eq. 5) (Claridge 2016c):

$$I_G = I_0 exp\left(-\frac{2\tau}{T_2}\right) exp\left((-\gamma\delta G)^2 D\left(\triangle - \frac{\delta}{3}\right)\right) \tag{5}$$

where I_0 is the signal in the absence of the gradient spin echo (i.e., that after a single 90° pulse), G is the gradient strength, D is the diffusion coefficient, δ the gradient pulse duration, and Δ the diffusion time. This equation forms the theoretical backbone of the pulsed gradient spin echo (PGSE) and stimulated echo (PFG-STE) sequences (Claridge 2016c), both widely used in food research. These diffusion sequences provide valuable insights into pore sizes, emulsion droplet radii, and macromolecular crowding in food matrices (Song 2009). For example, the restricted diffusion observed in starch gels (Ohtsuka et al. 1994; Doona et al. 2006) indicates structural confinement, while free diffusion in sugar syrups reflects molecular freedom in a homogeneous medium (Price et al. 2016).

In summary, the application of established NMR pulse sequences, such as inversion recovery for T_1, CPMG for T_2, and PGSE/PFG-STE for diffusion coefficients (D), enables the precise quantification of molecular dynamics within complex packaged food matrices. Rather than serving as mere physical abstractions, these parameters act as direct, non-invasive markers of food quality. Specifically, T_2 relaxation times serve as a sensitive probe for water mobility and syneresis, whereas T_1 measurements provide critical insights into fat distribution and the lipid state in emulsions. Furthermore, when these parameters are interpreted through their theoretical foundations, the measurements extend beyond empirical "fingerprinting" to offer a mechanistic view of food behavior, elucidating structural changes such as staling or the phase transitions of fats during storage. Consequently, by bridging the gap between molecular physics and macro-level properties like texture and stability, TD-NMR relaxometry becomes an indispensable tool for advancing quality control, precise formulation science, and accurate shelf-life prediction in the modern food industry.

NMR Instrumentation

The TD-NMR instrument, applied to packaged food analysis, has the same components as a standard high-resolution one. It is composed of a magnet, transmitter, receiver, probe, and a computer to control and signal processing. The major difference relies on the magnet and probe coils that have to be larger than the packaged food. Figure 2 shows "H" and Halbach permanent magnets with 80 and 100-mm probes, used in packaged food analysis. The "H" magnet was manufactured by Fine Instruments Technology (São Carlos, Brazil) and the Halbach by Spinlock (Cordoba Argentine).

An alternative approach operates on a unilateral or single-sided sensor, composed of a magnet and a probe as shown in Fig. 3. The magnet orientation can be configured either parallel or perpendicular to the sensor surface. Therefore, it allows the sensor for adjustable measurement depth within the investigated sample by modifying the position of the RF coil (Fig. 3) (Eidmann et al. 1996). In this array, the signal-to-noise ratio (SNR) diminishes with increased measurement depth, attributable to the B_1 stray field (Capitani et al. 2017). However, a limitation on the use of this device would be the low SNR, since it only uses stray magnetic fields. Unlike homogeneous low-field devices, like the Halbach array, inhomogeneous single-sided NMR systems expose samples to the stray magnetic field of the magnet. Therefore, they are classified as open-geometry systems (Capitani et al. 2017; Moraes and Colnago 2022). There are several other designs of unilateral NMR sensors, as shown elsewhere in the literature (Perlo et al. 2005; Stork et al. 2006; Veliyulin et al. 2008).

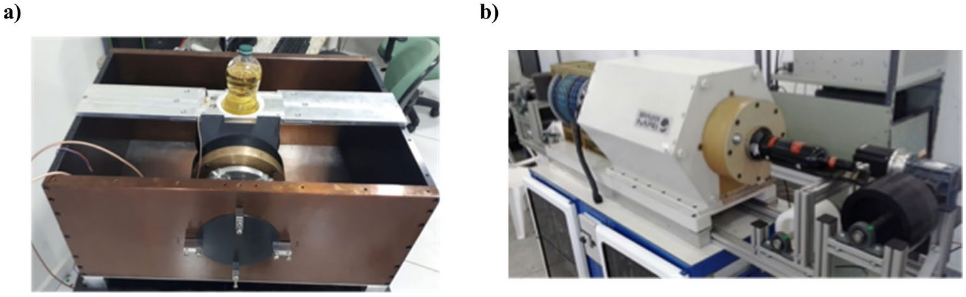

Fig. 2 TD-NMR devices with Halbach magnet array for the analysis of larger samples. These equipment feature a closed-geometry magnetic array with samples placed within a coil region in a uniform magnetic field. **a** Specfit HR 100 with resonance frequency of 4.2 MHz for ^{1}H. **b** Halbach Spinlock SKL-IF-1399 NMR spectrometer–resonance frequency of 9 MHz for ^{1}H. Own authorship image from NMR lab at Embrapa Instrumentação, São Carlos, Brazil

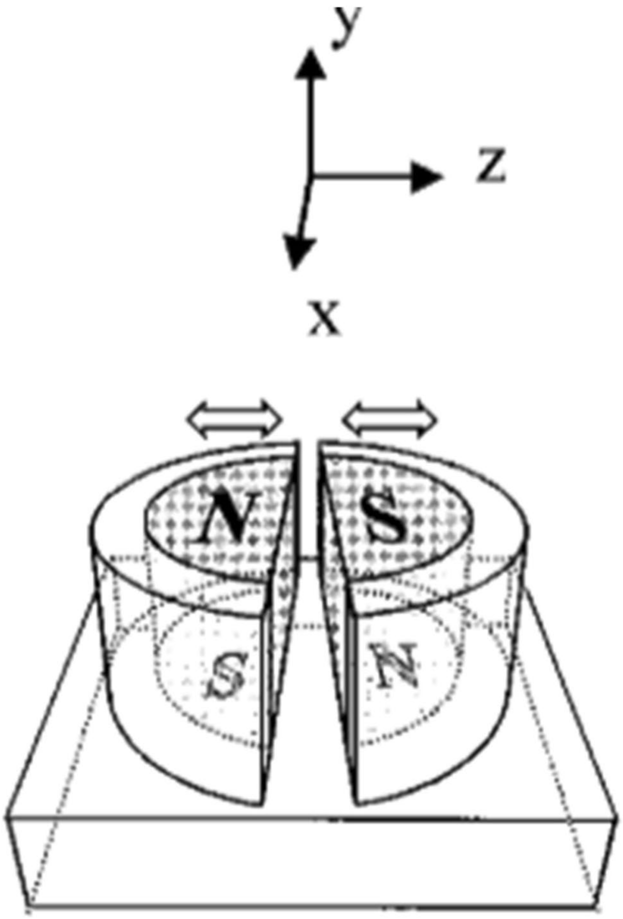

Fig. 3 Setup of the NMR-MOUSE probe. The design is constituted by two antiparallel magnets placed on an iron yoke, with the RF coil positioned in the gap between them. It operates with a strong magnetic field gradient in the frequency range of 13–18 MHz for the ^{1}H nucleus. Reprinted from Journal of Magnetic Resonance, Series A, Vol. 122, issue 1, G. Eidmann, R. Savelsberg, P. Blümler, B. Blümich, The NMR MOUSE, a Mobile Universal Surface Explorer, pages 104–109, Copyright (2025), with permission from Elsevier

TD-NMR Applications in Package Food

Literature on non-invasive TD-NMR measurements predominantly focuses on whole food products—including meat, fish, vegetables, and fruits—to evaluate physicochemical and structural properties of their primary constituents (e.g., water, fat, and proteins). Furthermore, there are also reports evaluating microbiological properties, and the use of both TD-NMR and LF-MRI applications for inline/online process control monitoring (Marcone et al. 2013; Fan and Zhang 2019). Regarding the latter, it produces images based on the relaxation time (T_1 or T_2) from proton spin density from water and lipids present on samples (Tang et al. 2019). We recommend taking a look at the review papers here addressed on TD-NMR assessments of whole foods for a thorough understanding of this matter (Marcone et al. 2013; Capitani et al. 2017; Kirtil et al. 2017; Fan and Zhang 2019; Ozel et al. 2021; Okere et al. 2021; Moraes and Colnago 2022).

In this section, we bring a few examples of TD-NMR (or LF-NMR) for the analysis of packaged food (Table 2). We divided the applications into dairy, edible oils, sauces, jam, and beverages. Besides the benchtop TD-NMR spectrometers presented in this section, Meyer et al. (2016) describe the current marketing situation for compact NMR spectrometers for industrial process control applications. Additionally, we recommend consulting the review by Giberson et al. (2021) which provides an overview of the leading commercial manufacturers of these instruments to facilitate a better understanding of the available practical options.

Dairy

Dairy products offer a rich source of proteins, fat, and minerals, occurring in liquid, semi-solid, and solid forms, such as in milk, cheese, ice cream, butter, and yogurt (van Duynhoven et al. 2010; Zhang and Bhatt 2014). An advantage of non-invasive TD-NMR measurements on dairy products is

Table 2 Papers reporting non-invasive analysis on TD-NMR (or LF-NMR) on packaged food products

Food category	Packaged food	Objective	Measurement	Reference
Dairy	Margarine and coffee cream	Demonstrate the capability of a single-sided NMR device on measuring fat content in oil/water emulsions	Diffusometry and relaxometry (spin echo pulse sequence)	Guthausen et al. (2004b)
	Whole cream milk, cereal cream, coffee cream, and whip cream*	Use a unilateral magnet array and water suppression pulse sequences to assess fat content on different dairy products	Diffusion stimulated echo CPMG (SE-CPMG) and CPMG	Veliyulin et al. (2008)
	Requeijão**	Determine moisture, fat and deffated dry mass content in commercial samples based on relaxometric profile	CPMG and CWFP-T_1	de Oliveira Machado et al. (2022)
Edible oils	Corn, canola, sunflower, soybean, hazelnut, and olive oil	Use a non-invasive TD-NMR procedure to detect olive oil adulteration with polyunsaturated vegetable oils in intact original bottle	CPMG	Santos et al. (2017)
Sauces	Tomato sauce	Determine if NMR spectroscopy is sensitive to tomato paste spoilage and to record the NMR signal from tomato paste in industrial, non-ferrous, metal-lined 1000-L totes	IR, CPMG, modified saturation recovery pulse sequence followed by CPMG	Pinter et al. (2014)
	Mayonnaise	Measure the fat content in packaged samples	CPMG	Verbi Pereira et al. (2015)
	Mustard sauce	Investigate the quality of mustard sauces inside of their sealed plastic packets	CPMG	Pereira et al. (2015)
Jam	Commercial strawberry, grape, guava, and raspberry jams	Develop calibration models based on non-invasive measurements to predict the amount of soluble solids content (SSC) (°Brix) and moisture in jams	CPMG	Santos and Colnago (2018)
Beverages	Bottles of oxygen-supersaturated table water, blueberry, white, and red wine	Test different approaches for a “single-sided” NMR sensor with a reduced magnetic field gradient	SR, echo Hahn	Stork et al. (2006)
	Whiskey and wine	Use of scalar coupling (J)-evolution during CPMG sequences to the acquisition of J-spectra of coupled spins	CPMG	Ronen and Webb (2023)
	Samples with different concentrations of ethanol in water (from 5 to 50% volume per volume), placed in a wine bottle, and white wine	Quantitatively estimate alcohol content in commercial samples	CPMG, IR	Moraes and Colnago (2022)

*Cereal cream and coffee creams were transferred to suitable glass flasks because of the aluminum layer covering the inner surface of the paperboard container. **Requeijão is a type of cream cheese prepared from the coagulation of pasteurized milk, with or without the addition of lactic cultures, followed by the addition of cream, water, and a melting salt, generally trisodium citrate (de Oliveira Machado et al. 2022) that it does not require the use of solvents. Besides, it is a time-saving technique (Veliyulin et al. 2008). However, liquid and semi-solid matrices represent a limitation for relaxometry profile acquisition due to abundant free (mobile) water (van Duynhoven et al. 2010). Alternatives for that may rely on assessing the system diffusometry profile or combining through echo pulse sequences. This alternative maximizes the contrast in their relaxation time.

In this context, Guthausen and coworkers did the very first attempt on a single-sided NMR device (Bruker) to evaluate the fat content in margarine and coffee cream. They tested acquiring both a diffusometry and relaxometry profile, the latter through an edited echo pulse sequence (Guthausen et al. 2004a). Fat content was determined by a calibration curve based on the different values assigned in the sample's packages *versus* the diffusometry or relaxometry measurement assessed. The correlation coefficient values for fat content in coffee cream (0.996) and in mayonnaise and margarines (0.991) demonstrated a great method performance. This approach was an advance towards industrial applications of TD-NMR systems for quality control measurements on packaged food. However, the use of open-geometry systems still is limited for its inherently low SNR.

Trying to overcome this issue, Veliyulin and coworkers assessed fat content in dairy products in a unilateral magnet array consisting of three block magnets all magnetized along the same directions (Fig. 4)—resonance frequency of 4.68 MHz for ^{1}H.

The pulse sequences used were a diffusion stimulated echo CPMG (SE-CPMG) and a regular CPMG pulse sequence. SE-CPMG was used to select only the stimulated echo contributions to the CPMG decay. Meanwhile, the authors used a 10 times lower relaxation delay time in the CPMG to enhance water T_1 suppression and diminish the fat component suppression. Data demonstrated a good linear correlation between experimental calculated amplitudes and the corresponding fat content indicated on the samples ($R^2 = 0.999$). Nevertheless, the approach used for water suppression, by reducing acquisition time, may also slightly suppress the fat component in dairy products. Modifications on the hardware in this latter approach proved to be an alternative for enhancing sensitivity on LF devices. Additionally, increasing the number of echoes in the fat content prediction is advantageous for improving SNR and thus the repeatability of the measurements (Veliyulin et al. 2008).

Oliveira and coworkers used an algorithm to predict moisture, fat, and defatted dry mass content in "requeijão" samples. The study used an SKL-IF-1399 NMR spectrometer–resonance frequency of 9 MHz for ^{1}H. Authors acquired CPMG and continuous wave free precession (CWFP-T_1) decay curves for the measurement of T_2 and T_1, respectively. CWFP-T_1 is a pulse sequence with a train of low flip angle pulses that allows the acquisition of long T_1 times within the same time for a CPMG acquisition (Monaretto et al. 2019). Samples demonstrated to have low, medium, and high moisture content based on the calculated T_1 and T_2 values. The decay observed in samples with higher moisture content resulted in higher T_1 and T_2 values. For correlating relaxation values with "requeijão" content, a partial least squares (PLS) model was used. It was calculated based on the T_1 and T_2 decay profiles, although regression models demonstrated reliable fitting only for CWFP-T_1 measurements (de Oliveira Machado et al. 2022). The comparison between classical methods (determination of defatted dry

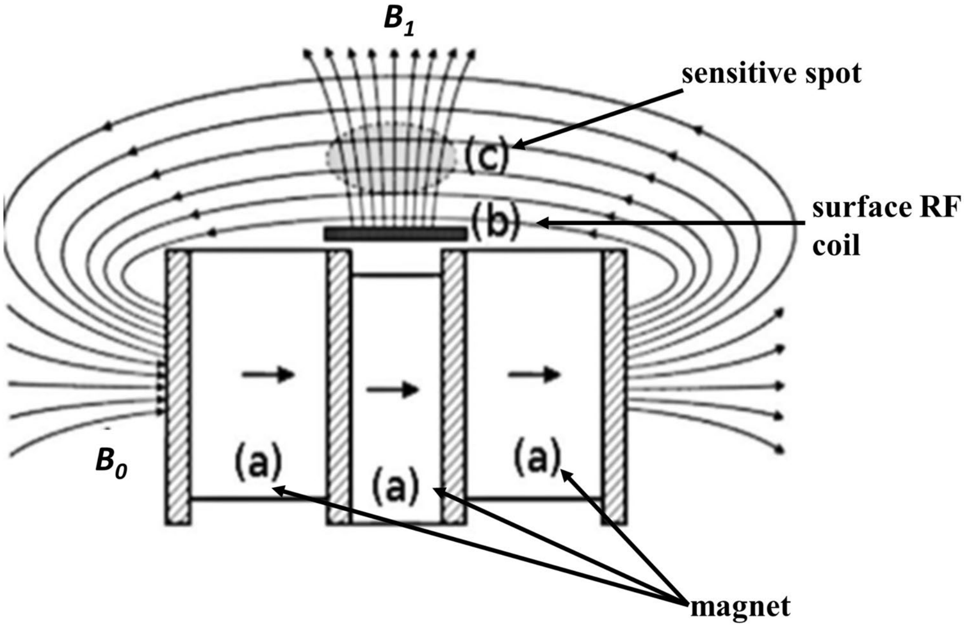

Fig. 4 Three magnet block array proposed by Veliyulin et al. **a**) The inner magnet is positioned slightly below the outer ones to produce a locally homogeneous magnetic field. **b**) RF coil. **c**) Sensitive spot to place the sample. Reproduced from Journal of The Science of Food and Agriculture, Vol. 88, September 2008, Emil Veliyulin, Igor V Mastikhin, Andrew E Marble, et al, Non-invasive analyses of packaged food using time domain NMR relaxometry, 2563-2567. Copyright (2008) (Veliyulin et al. 2008), with permission from John Wiley and Sons (License number: 6178171257996)

mass or moisture) and TD-NMR measurements performed by Oliveira and coworkers demonstrates a step towards the validation of TD-NMR as a standard method for the food industry.

Edible Oils

The International Organization for Standardization (ISO) since 2008 recognizes the use of TD-NMR for the determination of solid fat content in animal and vegetable oils as outlined in the normative standards ISO/CD 8292-1:2008 and ISO/CD 8292-2:2008 (International Organization for Standardization 2008a; 2008b). However, this standardized method only allows invasive measurements.

Furthermore, another important quality control parameter for edible oils is the oxidation status (Okere et al. 2021). The oxidation process generates volatile, low-molecular weight compounds that lead to structural changes in the oils. In this context, TD-NMR measurements provide valuable information concerning the supramolecular structure (e.g., triglycerides or fat acids content). This happens because of the intrinsic relation between relaxation times (T_1 and T_2) and molecular mobility (Osheter et al. 2022, 2023). As an example, Prestes and coworkers demonstrated correlation between viscosity and unsaturation for fatty acids with the same number of carbons. It was observed a decrease in viscosity when a fatty acid or a triacyl glycerol presented more unsaturation (Prestes et al. 2007). Moreover, Santos and coworkers tested a non-invasive TD-NMR procedure to detect olive oil adulteration with cheaper polyunsaturated vegetable oils in intact original bottles (Santos et al. 2017). Olive oil is defined as the oil obtained solely from the fruit of *Olea europaea L.* through mechanical methods or other physical processes that do not modify the glyceric structure of the oil and maintain its distinctive properties (Alonso-Salces et al. 2010b). Regarding its composition, it mainly contains triglycerides (more than 98%) and an unsaponifiable fraction (1–2%) (Alonso-Salces et al. 2010a). The samples analyzed were corn, canola, sunflower, soybean, hazelnut, and olive oil by CPMG pulse sequence in a 0.23 T SLK-IF-1399 NMR spectrometer (Spinlock Magnetic Resonance Solution, Cordoba, Argentina). In order to compare T_2 measurements with oil adulteration, authors initially determined the ratio between the areas corresponding to the signals at 2.3 and 4.9–5.4 ppm obtained by ^{1}H NMR. These signals correspond to fat acids and unsaturated fat acid regions, respectively. Authors observed that in samples that presented a ratio greater than 0.2, the T_2 values were also higher than the other samples. These last set of samples consisted of corn, canola, sunflower, soybean commercial oils, and blends of olive oil and soybean, canola, sunflower, and corn oils. Most of the commercial extra virgin olive oil and hazelnut oil samples presented T_2 values below 0.11 s, demonstrating low polyunsaturated fatty acid content. Authors suggested that the ones that presented higher values for this parameter may contain a possible adulteration with soybean oil or other polyunsaturated oils. A principal components analysis (PC1 = 84.0% and PC2 13.8%) was performed in order to try to find clustering patterns within the full T_2 relaxation curves. Three groups were observed: virgin olive oil and hazelnut oil (samples with T_2 lower than 0.11 s), polyunsaturated oils (corn, canola, sunflower, and soybean), and the possible adulterated virgin olive oil samples. Accordingly, authors could discriminate between olive oil adulterated with high contents of polyunsaturated oil in their intact commercial bottles (Santos et al. 2017). While effective for detecting gross adulteration with polyunsaturated oils, T_2-based measurements may struggle to identify sophisticated adulterants with relaxation times similar to olive oil. Future work could focus on combining T_1 and T_2 in a 2D relaxometry approach, measured at several temperatures, which may help to improve specificity.

Sauces

The *Codex Alimentarius* categorizes sauces as a type of condiment added to food to enhance aroma and taste. This type of food is, however, susceptible to spoilage in the manufacturing and/or storage process. Interested in determining if NMR relaxometry is sensitive to tomato paste spoilage and to record the NMR signal from tomato paste in industrial, non-ferrous, metal-lined 1000-L totes, Pinter and coworkers designed a single-sided NMR device to measure this effect in a metal container. Initially, the authors measured an aliquot of 100mL of tomato sauce in a 4 MHz TD-NMR, through IR and CPMG, to investigate how to correlate the tomato sauce relaxation profile to spoilage. For this measurement, it was evaluated the relaxometry profile of sterile and non-sterile tomato sauce samples at room temperature. Non-sterile samples presented changes in their decay curves, compared to sterile ones, probably related to changes in the substrate matrix. Then, they connected a Tecmag Redstone NMR spectrometer to an ABQMR single-sided permanent magnet system, operating at 5.25 MHz for the ^{1}H frequency. For this device, they used a modified saturation recovery pulse sequence that incorporated a ± 75 kHz frequency sweep into the saturation pulse followed by a CPMG pulse sequence to obtain T_1 and T_2. From the initial measurements, comparing sterile samples and bacterial-spoilage ones, they were able to relate an increase in the steady-state spin lattice relaxation time with a decrease in sample viscosity. Then, when proceeding to the measurements in the containers, the values of T_1 were consistent with sterile samples (Pinter et al. 2014).

Packaged mayonnaise and salad dressing sauces were analyzed by Pereira and coworkers to determine its fat content. The experiments were performed in a 0.23 T Halbach permanent magnet (9 MHz for ^{1}H frequency) using CPMG pulse sequence. The relaxation profile in samples demonstrated differences based on the sample (mayonnaise or salad dressing) and in the total fat content. For the salad dressings, the high-water content influenced higher T_2 values when compared to mayonnaise samples. A PLS model presented a good fit ($R^2 = 0.97$) relating the T_2 decay and the fat content determined by Bligh and Dyer's method for each type of sample (Verbi Pereira et al. 2015).

Mustard sauces are a preparation from mustard seed, water, vinegar, salt, oil, and spices (García-Casal et al. 2016). Pereira and coworkers in order to investigate the quality of this product in their sealed packages performed an analysis on ten samples from the local market. The analysis was conducted in an NMR spectrometer with a wide-bore 0.23 T Halbach permanent magnet. The CPMG pulse sequence was used to acquire relaxation information. The decay signal was then correlated with the sample's moisture content and soluble solid content (SSC). Data demonstrated a good correlation ($R = 0.8$, R^2 not provided) when comparing T_2 decay with the value of moisture content and SSC measured by standard methods. Furthermore, the authors demonstrated that samples with low moisture content had a higher SSC content and a shorter T_2 (Pereira et al. 2015).

Current validated methods require invasive and time-consuming measurements, which add a cost for food industry practices, such as the Bligh and Dyer's or SSC method. TD-NMR hardware adaptation and the correlation of physicochemical/microbiological parameters with relaxation times are a step forward to inline quality control methods implementation.

Jam

Produced to reduce fruit spoilage and enhance its availability to consumers during the off-season, jam is described by the Codex Alimentarius as "the product brought to a suitable consistency, made from the whole fruit, pieces of fruit, the unconcentrated and/or concentrated fruit pulp or fruit puree of one or more kinds of fruit, mixed with foodstuffs with sweetening properties, with or without the addition of water" (Codex 2009).

The study of Santos and coworkers explored different non-invasive procedures to develop calibration models based to predict the amount of soluble solids content (SSC) (°Brix) and moisture in jams. The authors compared standard methods reported in the Association of Official Analytical Chemists (AOCS) for SSC (°Brix) and moisture determination with mid-infrared (MIR), near-infrared (NIR), and LF-NMR measurements. LF-NMR measurements take place in a SLK 100 TD-NMR benchtop spectrometer (Spinlock Magnetic Resonance Solution, Cordoba, Argentine) with a permanent magnet of 8.9 MHz for ^{1}H frequency. Samples had their T_2 profile assessed by CPMG pulse sequence. Data presented a correlation between T_2 and SSC (°Brix) similar to the one presented for Pereira et al. (2013). This happens due to the inverse correlation to sample's viscosity, that increases with sugar content, and a lower T_2. Therefore, jams with higher sugar concentrations (traditional jams) exhibited significantly lower T_2 values compared to samples with lower sugar content (diet, light, and no sugar added jams). Authors suggest that an increase in SSC (°Brix) restricts the mobility of water molecules due to interactions with sugar hydroxyl groups, resulting in reduced relaxation times. Although it was possible to correlate these parameters, the authors' findings demonstrated that MIR and NIR regression models, for the evaluated samples, were still more accurate when compared with TD-NMR ones (Santos and Colnago 2018).

While this study and others successfully use TD-NMR data in multivariate models like PLS, a critical comparison with MIR/NIR highlights a fundamental limitation of TD-NMR: its input data. TD-NMR provides a time-domain relaxation decay, which is excellent for quantifying global physical states (e.g., moisture content, solid fat content) but is a low-information-density signal compared to a vibrational spectrum. MIR and NIR spectra contain numerous absorption bands directly correlated to specific chemical bonds (e.g., O-H, C-H). This allows PLS models built on spectral data not only to predict parameters but also to identify which chemical components are driving the correlation, offering a level of interpretability that TD-NMR models inherently lack. Nevertheless, the biggest benefit of TD-NMR compared with MIR/NIR still relies on its capability to directly analyze samples placed in glass or plastic containers.

Beverages

The study of Stork, Gädke, and Nestle was one of the very first TD-NMR experiments on unopened beverage bottles. They used bottles of oxygen-supersaturated table water, measuring T_2 by CPMG. Conversely, they evaluated blueberry, white, and red wine, measuring T_1 by saturation-recovery pulse sequence. They acquired data on different single-sided equipment, including a home-built semisingle-sided device. Data showed that SNR was very similar in both devices, based on oxygen concentration calibration curves. They also tested that the semisingle-sided device could measure oxygen loss after the opening of the bottles, by measuring the relaxation time every 22 min. T_1 measurements were used as a proof-of-concept on these measurements in the home-built device. Authors attributed the different T_1 relaxation times to dissolved paramagnetic Mn^{2+} ions (Marcone et al. 2013). This study demonstrates TD-NMR's unique value. In a beverage, the relaxation decay is not just a proxy for water content but a direct measurement of water mobility, which is governed by its interactions with solutes. Lastly, rather than focusing on resolving overlapping spectral lines through the development of increasingly advanced self-shielding magnet systems with higher field strengths, Ronen and Webb concentrated on applying a CPMG pulse sequence with long echo time that is modulated by the spin-spin coupling or J-coupling. As the J-coupling is independent of magnetic field strength, they performed the experiments in a home-built LF-MRI ($B_0 = 0.046$ T, with 1.96 MHz for ^{1}H frequency), with a 31-cm diameter bore (Fig. 5) (Ronen and Webb 2023; Webb et al. 2023).

The high-resolution J-spectra of coupled spins were successfully acquired through the Fourier transform of a series of echoes generated via a CPMG sequence. This approach offers a significant advantage by preserving vital information regarding spin-spin couplings that are typically obscured by field inhomogeneity in standard low-field experiments (Ronen and Webb 2023). Furthermore, experimental data confirmed that the peak distributions in the analyzed samples closely matched previous simulations, thereby validating the robustness of the sequence. Nevertheless, the application of J-spectroscopy at low fields involves inherent limitations that must be addressed. A primary challenge is solvent dominance, as real-world samples typically exhibit a significant non-coupled water signal; this results in a prominent zero-frequency peak that can overshadow weaker resonances from solutes. Additionally, while the CPMG-based approach effectively removes inhomogeneous broadening, the lower signal-to-noise ratio (SNR) characteristic of low-field hardware remains a constraint. This is further compounded by the fact that at lower field strengths, the proximity of different chemical shifts can lead to complex second-order coupling effects, rendering spectral interpretation more difficult than at high fields. To mitigate these challenges and enhance quantification accuracy, Linear Prediction Singular Value Decomposition (LPSVD) was employed to estimate integrated intensities, specifically for determining ethanol concentrations. Despite the presence of the dominant water signal, a linear regression based on LPSVD estimation correctly predicted the alcoholic concentration of a bottled wine sample (Webb et al. 2023). Ultimately, these findings demonstrate that when combined with appropriate post-processing techniques, the limitations of low-field J-spectroscopy can be effectively managed for practical quality control applications in the food and beverage industry.

NMR Non-invasive Analysis: Successes, Limitations, and Paths Forward

Low-field NMR overcomes the fundamental challenge of analyzing complex packaged foods by providing a rapid, non-destructive method to directly measure critical quality parameters. For instance, the examples provided here illustrate these features, such as the fat quantification in requeijão by CWFP-T_1 or in mayonnaise by CPMG (de Oliveira Machado et al. 2022; Verbi Pereira et al. 2015). Moreover,

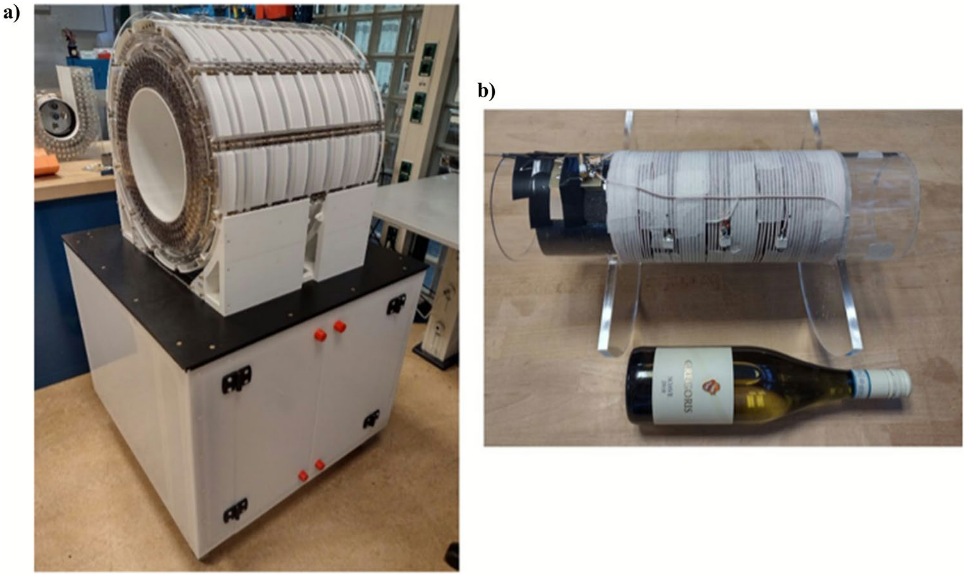

Fig. 5 **a**) The 46 mT portable Halbach-based MRI system, with its electronics housed in the cabinet below. Shim trays encircle the magnet. **b**) The segmented solenoid transmit/receive coil positioned alongside a wine bottle, with plastic supports ensuring precise centering within the magnet. Reproduced from Webb, A.; Najac, C.; Ronen, I. Rapid Quantification of Alcohol Content in Intact Bottles of Wine Using Scalar-Coupled Spectroscopy at Low Field. *Appl. Magn. Reson.* 2023,*54*, 1321–1328, doi:10.1007/s00723-023-01585-0 (Webb et al. 2023).This is an open access article distributed under the terms of the Creative Commons CC BY license, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

the literature has demonstrated how T_1 and T_2 can be correlated with viscosity, °Brix, and fat content (Prestes et al. 2007; Santos and Colnago 2018; Guthausen et al. 2004a). Establishing these correlations not only demonstrates the versatility of time-domain NMR (TD-NMR) across different food categories but also adds significant value to the method as an industrial tool (Santos and Colnago 2018).

However, despite the robustness of TD-NMR procedures, distinguishing similar oils based solely on T_2 can be ambiguous, a clear manifestation of the challenges posed by overlapping relaxation times. To address this, 2D correlation techniques have become critical for future advancements. Nevertheless, a central challenge remains: while these experiments offer high resolution, the complexity of data processing often hinders their adoption in routine industrial practice. Conversely, there has been a notable rise in the application of machine learning and deep learning algorithms, such as multivariate curve resolution and parallel factor analysis, to process complex TD-NMR data (Galvan et al. 2023). Ultimately, the integration of advanced relaxation experiments with these chemometric algorithms represents a promising path forward for embedding TD-NMR into effective industrial workflows.

In addition to processing constraints, low sensitivity remains a fundamental limitation for both benchtop and portable LF-NMR devices. Consequently, ongoing research is actively focused on overcoming this hurdle to enhance performance for in situ measurements and industrial sensor applications (Hills 2006). Specifically, Utsuzawa and Fukushima (2017) developed a portable device utilizing a barrel magnet to address these constraints. Similarly, Oliveira-Silva et al. (2021) contributed to the field by developing a single-sided benchtop well-logging magnet.

In a different approach to geometry, Utsuzawa and Fukushima designed an open-access Halbach magnet consisting of an axially magnetized hollow cylinder paired with two identical, parallel bar magnets (Fig. 6a). This configuration ensures that the magnetic field within the cylinder's hollow is oriented opposite to the axial field at a distance (Fig. 6b). Consequently, this setup creates a magnetic field "saddle point"—a local maximum along the axial direction and a local minimum in the radial direction—positioned just off

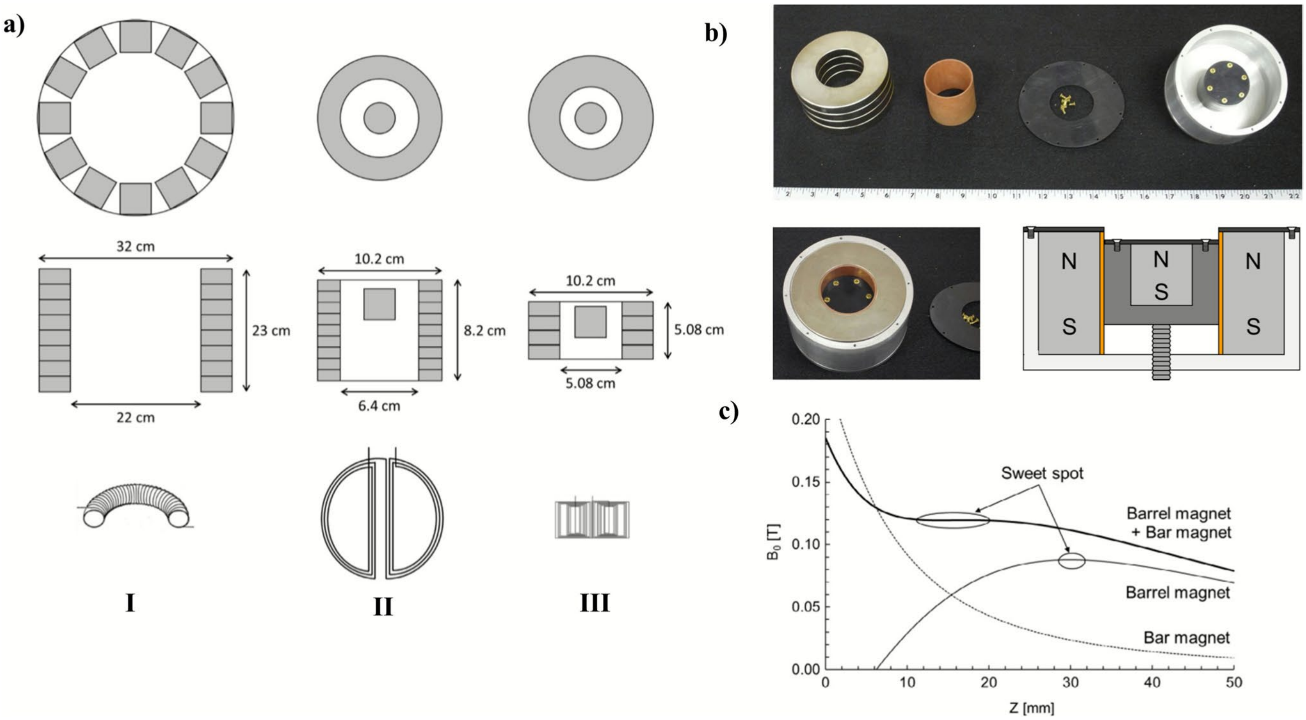

Fig. 6 Barrel magnet design including magnet geometry, cross-sectional drawing of the assembly and field profile adjustment to find the two magnets sweet spot proposed by Utsuzawa & Fukushima. **aI**) hollow cylinder made with distinct columns of magnetic materials. aII) magnet made from 9 rings by NEOMAX, used with a double-D shaped gradiometer coil. aIII) magnet B made from 4 rings used with a modified figure-eight coil. **b**) from left to right, the NdFeB ring magnet stack, a thin Delrin sleeve that facilitates the sliding movement of the bar magnet assembly, a hard-plastic cover, and the aluminum holder with the bar magnet assembly installed. **c**) Calculated field profiles along the barrel and bar magnets' axes of symmetry, denoted by Z. Reproduced from Journal of Magnetic Resonance, Vol. 282, September 2017, Shin Utsuzawa, Eiichi Fukushima, Unilateral NMR with a barrel magnet, 104-113. Copyright (2025) (Utsuzawa and Fukushima 2017), with permission from Elsevier (License number: 6075680011463).

the end of the cylinder (Fig. 6c) (Utsuzawa & Fukushima 2017).

Parallel to these developments, Oliveira-Silva and coworkers described a single-sided device with a magnetic field perpendicular to the magnet's surface, utilizing two probes operating at 2 MHz. The first probe, a 26-turn solenoid coil, is designed for cylindrical samples up to 44 mm in diameter and focuses on maximizing sensitivity via a homogeneous $\mathbf{B}_1$ field. In contrast, the second probe, an eight-shaped planar surface coil, generates a sensitive region outside the probe itself, allowing for the analysis of samples with unrestricted shapes. Although the authors initially tested this device on oil samples, they suggest its potential for broader use in the agricultural and food industries (de Oliveira-Silva et al. 2021).

Furthermore, the open-access Halbach magnet array proposed by Hills and coworkers represents a significant shift in sample accessibility. By using four dipole magnets spaced relative to the field center, this configuration achieves a moderately homogeneous field without the tight confinement of traditional pole pieces. Furthermore, the integration of a flat solenoid RF coil allows the system to function as a surface coil, enabling the analysis of large samples. Ultimately, this design offers improved $\mathbf{B}_0$ homogeneity compared to standard MOUSE NMR arrays, facilitating the excitation of significantly larger sample volumes (Hills et al. 2005).

Ultimately, regarding the use of LF-MRI devices for packaged food analysis, it has the advantage of handling larger samples than benchtop and portable TD-NMR equipment. Even though J-spectroscopy on such devices still faces a few challenges, potential solutions applying post-processing methods are an alternative for qualitative measurements on LF-MRI. Considering such limitations, we believe that the implementation of a J-refocused CPMG sequence for spectra acquisition seems to be the next step towards J-coupling measurements in LF-MRI devices.

Conclusions

The continuous development of more compact, user-friendly low-field NMR systems, paired with advancements in data processing like machine learning, is set to deeply integrate this technology across the entire food supply chain. This means low-field NMR's relaxation and diffusion measurements will become increasingly common in modern food science and industry, from assessing raw materials and optimizing processes to monitoring shelf-life and verifying authenticity.

Ultimately, TD-NMR is poised to transform how we analyze packaged food. Its non-invasive nature, ease of operation, and the comprehensive information it provides make it an invaluable technique. In future perspectives, this also means consumers will be able to easily and straightforwardly analyze their own packaged food products using TD-NMR spectrometers. This will significantly enhance safety, quality, and supply chain transparency for a wide range of food products.

Author Contribution L. S. A., F. V. C. K. and L. A. C. contributed equally with conceptualization, methodology, writing—original draft preparation; writing—review and editing. All authors have read and agreed to the published version of the manuscript. L. L. B. contributed with writing—review and editing.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of Interest The authors declare no competing interests.

References

Aboud SA, Altemimi AB, R S Al-HiIphy A et al (2019) A comprehensive review on infrared heating applications in food processing. Molecules 24:4125. https://doi.org/10.3390/molecules24224125

Alekseev GV, Khripov AA (2015) Method of rapid remote control of casein concentration in dairy products in unopened packages. J Food Process Eng 38:11–18. https://doi.org/10.1111/jfpe.12121

Alonso-Salces RM, Héberger K, Holland MV et al (2010) Multivariate analysis of NMR fingerprint of the unsaponifiable fraction of virgin olive oils for authentication purposes. Food Chem 118:956–965. https://doi.org/10.1016/j.foodchem.2008.09.061

Alonso-Salces RM, Moreno-Rojas JM, Holland MV et al (2010) Virgin olive oil authentication by multivariate analyses of 1H NMR fingerprints and δ13C and δ2H data. J Agric Food Chem 58:5586–5596. https://doi.org/10.1021/jf903989b

Beć KB, Grabska J, Huck CW (2022) Miniaturized NIR spectroscopy in food analysis and quality control: promises, challenges, and perspectives. Foods 11:1465. https://doi.org/10.3390/foods11101465

Ben Akacha B, Madureira J, Cabo Verde S et al (2025) Advances in cheese safety and quality: harnessing irradiation technologies for enhanced preservation. J Food Sci Technol 62:433–452. https://doi.org/10.1007/s13197-024-06190-y

Boyd J, Soffe N, Campbell I (1994) NMR at very high fields. Structure 2:253–255. https://doi.org/10.1016/S0969-2126(00)00027-7

Capitani D, Sobolev AP, Di Tullio V et al (2017) Portable NMR in food analysis. Chem Biol Technol Agric 4:17. https://doi.org/10.1186/s40538-017-0100-1

Claridge TDW (2016a) Chapter 2 - Introducing high-resolution NMR. In: Claridge TDW (ed) High-resolution NMR techniques in organic chemistry, 3rd edn. Elsevier, Boston, pp 11–59

Claridge TDW (2016b) Chapter 3 - Practical aspects of high-resolution NMR. In: Claridge TDW (ed) High-resolution NMR techniques in organic chemistry, 3rd edn. Elsevier, Boston, pp 61–132

Claridge TDW (2016c) Chapter 10 - Diffusion NMR spectroscopy. In: Claridge TDW (ed) High-resolution NMR techniques in organic chemistry, 3rd edn. Elsevier, Boston, pp 381–419

CODEX (2009) Codex Standard 296 Standard for Jams. Jellies and Marmalades. - References - Scientific Research Publishing. https://www.scirp.org/reference/referencespapers?referenceid=776859. Accessed 13 Oct 2025

Colnago LA, Azeredo RBV, Marchi Netto A et al (2011) Rapid analyses of oil and fat content in agri-food products using continuous wave free precession time domain NMR. Magn Reson Chem 49(Suppl 1):S113–S120. https://doi.org/10.1002/mrc.2841

Colsenet R, Mariette F, Cambert M (2005) NMR relaxation and water self-diffusion studies in whey protein solutions and gels. J Agric Food Chem 53:6784–6790. https://doi.org/10.1021/jf050162k

Curti E, Anedda R (2023) TD-NMR as a quality control tool for dairy products: a study on Fiore Sardo PDO cheese. Food Bioprocess Technol 16:459–465. https://doi.org/10.1007/s11947-022-02947-5

de Oliveira Machado G, Teixeira GG, Garcia RH dos S et al (2022) Non-invasive method to predict the composition of Requeijão Cremoso directly in commercial packages using time domain NMR relaxometry and chemometrics. Molecules 27:4434. https://doi.org/10.3390/molecules27144434

de Oliveira-Silva R, Lucas-Oliveira É, de Araújo-Ferreira AG et al (2021) A benchtop single-sided magnet with NMR well-logging tool specifications – examples of application. J Magn Reson 322:106871. https://doi.org/10.1016/j.jmr.2020.106871

Doona CJ, Feeherry FE, Baik M-Y (2006) Water dynamics and retrogradation of ultrahigh pressurized wheat starch. J Agric Food Chem 54:6719–6724. https://doi.org/10.1021/jf061104h

Eccles C (2010) Low field NMR methods and applications. In: Lindon JC (ed) Encyclopedia of spectroscopy and spectrometry, 2nd edn. Academic Press, Oxford, pp 1357–1371

Eidmann G, Savelsberg R, Blümler P, Blümich B (1996) The NMR mouse, a mobile universal surface explorer. J Magn Reson Ser A 122:104–109. https://doi.org/10.1006/jmra.1996.0185

Ezeanaka MC, Nsor-Atindana J, Zhang M (2019) Online low-field nuclear magnetic resonance (LF-NMR) and magnetic resonance imaging (MRI) for food quality optimization in food processing. Food Bioprocess Technol 12:1435–1451. https://doi.org/10.1007/s11947-019-02296-w

Fakhar HI, Cavdaroglu E, Hayat MQ et al (2024) Exploring noncentrifugal sugar as a partial replacement for white sugar in low methoxyl pectin confectionery gels: impacts on physical and rheological properties. ACS Food Sci Technol 4:3036–3046. https://doi.org/10.1021/acsfoodscitech.4c00603

Fan K, Zhang M (2019) Recent developments in the food quality detected by non-invasive nuclear magnetic resonance technology. Crit Rev Food Sci Nutr 59:2202–2213. https://doi.org/10.1080/10408398.2018.1441124

Galvan D, de Aguiar LM, Bona E et al (2023) Successful combination of benchtop nuclear magnetic resonance spectroscopy and chemometric tools: a review. Anal Chim Acta 1273:341495. https://doi.org/10.1016/j.aca.2023.341495

García-Casal MN, Peña-Rosas JP, Malavé HG (2016) Sauces, spices, and condiments: definitions, potential benefits, consumption patterns, and global markets. Ann N Y Acad Sci 1379:3–16. https://doi.org/10.1111/nyas.13045

Giberson J, Scicluna J, Legge N, Longstaffe J (2021) Developments in benchtop NMR spectroscopy 2015–2020. In: Annual Reports on NMR Spectroscopy. Academic Press Inc., pp 153–246. https://doi.org/10.1016/bs.arnmr.2020.10.006

Gomes H, Navio F, Gaspar PD et al (2023) Radio-frequency identification traceability system implementation in the packaging section of an industrial company. Appl Sci 13:12943. https://doi.org/10.3390/app132312943

Gorman J (2002) Wine tasting: instrument can sniff out vinegar in sealed wine. Sci News 162:150–150. https://doi.org/10.2307/4013765

Goudappel GJW, van Duynhoven JPM, Mooren MMW (2001) Measurement of oil droplet size distributions in food oil/water emulsions by time domain pulsed field gradient NMR. J Colloid Interface Sci 239:535–542. https://doi.org/10.1006/jcis.2001.7603

Guthausen A, Guthausen G, Kamlowski A et al (2004) Measurement of fat content of food with single-sided NMR. J Am Oil Chem Soc 81:727–731. https://doi.org/10.1007/s11746-004-0969-5

Haddad L, Francis J, Rizk T et al (2022) Cheese characterization and authentication through lipid biomarkers obtained by high-resolution 1H NMR profiling. Food Chem 383:132434. https://doi.org/10.1016/j.foodchem.2022.132434

Haiduc AM, van Duynhoven J (2005) Correlation of porous and functional properties of food materials by NMR relaxometry and multivariate analysis. Magn Reson Imaging 23:343–345. https://doi.org/10.1016/j.mri.2004.11.047

Hills BP (2006) Applications of low-field NMR to food science. Annual reports on NMR spectroscopy 58:177–230. https://doi.org/10.1016/S0066-4103(05)58004-9

Hills BP, Wright KM, Gillies DG (2005) A low-field, low-cost Halbach magnet array for open-access NMR. J Magn Reson 175:336–339. https://doi.org/10.1016/j.jmr.2005.04.015

Hopkins EJ, Newling B, Hucl P et al (2019) Water mobility and association by 1H NMR and diffusion experiments in simple model bread dough systems containing organic acids. Food Hydrocoll 95:283–291. https://doi.org/10.1016/j.foodhyd.2019.04.018

Hoult DI, Richards RE (1976) The signal-to-noise ratio of the nuclear magnetic resonance experiment. Journal of Magnetic Resonance (1969) 24:71–85. https://doi.org/10.1016/0022-2364(76)90233-X

International Organization for Standardization (2008a) ISO/CD 8292–1:2008: animal and vegetable fats and oils - determination of solid fat content by pulsed NMR. Part 1: direct method. ISO, Geneva

International Organization for Standardization (2008b) ISO/CD 8292–2:2008: animal and vegetable fats and oils - determination of solid fat content by pulsed NMR. Part 2: indirect method. ISO, Geneva

Ioannidis GS, Nikiforaki K, Kalaitzakis G et al (2020) Inverse Laplace transform and multiexponential fitting analysis of T2 relaxometry data: a phantom study with aqueous and fat containing samples. Eur Radiol Exp 4:28. https://doi.org/10.1186/s41747-020-00154-5

Jiao Y, Tang J, Wang Y, Koral TL (2018) Radio-frequency applications for food processing and safety. Annu Rev Food Sci Technol 9:105–127. https://doi.org/10.1146/annurev-food-041715-033038

Kandasamy S, Park W-S, Bae I-S et al (2024) HRMAS-NMR-based metabolomics approach to discover key differences in cow and goat milk yoghurt metabolomes. Foods 13:3483. https://doi.org/10.3390/foods13213483

Kharbanda Y, Mailhiot S, Mankinen O et al (2023) Monitoring cheese ripening by single-sided nuclear magnetic resonance. J Dairy Sci 106:1586–1595. https://doi.org/10.3168/jds.2022-22458

Kirtil E, Cikrikci S, McCarthy MJ, Oztop MH (2017) Recent advances in time domain NMR & MRI sensors and their food applications. Curr Opin Food Sci 17:9–15. https://doi.org/10.1016/j.cofs.2017.07.005

Laghi L, Venturi L, Dellarosa N, Petracci M (2017) Water diffusion to assess meat microstructure. Food Chem 236:15–20. https://doi.org/10.1016/j.foodchem.2016.12.043

Lee J-G, Lee Y, Kim CS, Han SB (2021) Codex alimentarius commission on ensuring food safety and promoting fair trade: harmonization of standards between Korea and codex. Food Sci Biotechnol 30:1151–1170. https://doi.org/10.1007/s10068-021-00943-7

Levitt MH (2008) Spin dynamics: basics of nuclear magnetic resonance, 2nd edn. Wiley, Chichester

Li Q, Xiang J (2025) Applications of high-field nuclear magnetic resonance (NMR) in chemical research. J Magn Reson Open 23:100199. https://doi.org/10.1016/j.jmro.2025.100199

Ma S, Li R, Li Q et al (2022) Pilot-scale radio frequency-assisted pasteurization of chili powders prepacked by different packaging films. Sustainability 14:9132. https://doi.org/10.3390/su14159132

Maestro D, Šegalo S, Pašalić A et al (2022) Food safety – from pioneering steps to the modern scientific discipline. Journal of Health Sciences 12:178–183. https://doi.org/10.17532/jhsci.2022.1914

Marcone MF, Wang S, Albabish W et al (2013) Diverse food-based applications of nuclear magnetic resonance (NMR) technology. Food Res Int 51:729–747. https://doi.org/10.1016/j.foodres.2012.12.046

Marigheto N, Venturi L, Hills B (2008) Two-dimensional NMR relaxation studies of apple quality. Postharvest Biol Technol 48:331–340. https://doi.org/10.1016/j.postharvbio.2007.11.002

Métais A, Mariette F (2003) Determination of water self-diffusion coefficient in complex food products by low field ^{1}H PFG-NMR: comparison between the standard spin-echo sequence and the T1-weighted spin-echo sequence. J Magn Reson 165:265–275. https://doi.org/10.1016/j.jmr.2003.09.001

Meyer K, Kern S, Zientek N et al (2016) Process control with compact NMR. TrAC Trends Anal Chem 83:39–52. https://doi.org/10.1016/j.trac.2016.03.016

Mitchell J, Gladden LF, Chandrasekera TC, Fordham EJ (2014) Low-field permanent magnets for industrial process and quality control. Prog Nucl Magn Reson Spectrosc 76:1–60. https://doi.org/10.1016/j.pnmrs.2013.09.001

Monaretto T, Andrade FD, Moraes TB et al (2015) On resonance phase alternated CWFP sequences for rapid and simultaneous measurement of relaxation times. J Magn Reson 259:174–178. https://doi.org/10.1016/j.jmr.2015.08.013

Monaretto T, Souza A, Moraes TB et al (2019) Enhancing signal-to-noise ratio and resolution in low-field NMR relaxation measurements using post-acquisition digital filters. Magn Reson Chem 57:616–625. https://doi.org/10.1002/mrc.4806

Moraes TB, Colnago LA (2022) Noninvasive analyses of food products using low-field time-domain NMR: a review of relaxometry methods. Braz J Phys 52:43. https://doi.org/10.1007/s13538-022-01055-1

Moraes TB, Monaretto T, Colnago LA (2016) Rapid and simple determination of relaxation times in time-domain NMR by continuous wave free precession sequence. J Magn Reson 270:1–6. https://doi.org/10.1016/j.jmr.2016.06.019

Motarjemi Y, Warren BR (2023) Hazard analysis and critical control point system (HACCP). In: Food safety management. Elsevier, pp 799–818. https://doi.org/10.1016/B978-0-12-820013-1.00017-6

Musio B, Ragone R, Todisco S et al (2024) Non-targeted nuclear magnetic resonance analysis for food authenticity: a comparative study on tomato samples. Molecules 29:4441. https://doi.org/10.3390/molecules29184441

Musse M, Challois S, Huc D et al (2014) MRI method for investigation of eye growth in semi-hard cheese. J Food Eng 121:152–158. https://doi.org/10.1016/j.jfoodeng.2013.08.010

Nelson SO (2008) Dielectric properties of agricultural products and some applications. Res Agric Eng 54:104–112. https://doi.org/10.17221/1000-RAE

Nikolaeva T, Rietkerk T, Sein A et al (2020) Impact of water degumming and enzymatic degumming on gum mesostructure formation in crude soybean oil. Food Chem 311:126017. https://doi.org/10.1016/j.foodchem.2019.126017

Ohtsuka A, Watanabe T, Suzuki T (1994) Gel structure and water diffusion phenomena in starch gels studied by pulsed field gradient stimulated echo NMR. Carbohydr Polym 25:95–100

Okere EE, Arendse E, Nieuwoudt H et al (2021) Non-invasive methods for predicting the quality of processed horticultural food products, with emphasis on dried powders, juices and oils: a review. Foods 10:3061. https://doi.org/10.3390/foods10123061

Osheter T, Linder C, Wiesman Z (2022) Time domain (TD) proton NMR analysis of the oxidative safety and quality of lipid-rich foods. Biosensors (Basel) 12:230. https://doi.org/10.3390/bios12040230

Osheter T, Campisi Pinto S, Randieri C et al (2023) Semi-autonomic AI lf-NMR sensor for industrial prediction of edible oil oxidation status. Sensors 23:2125. https://doi.org/10.3390/s23042125

Ozel B, Kruk D, Wojciechowski M et al (2021) Water dynamics in whey-protein-based composite hydrogels by means of NMR relaxometry. Int J Mol Sci 22:9672. https://doi.org/10.3390/ijms22189672

Pedersen HT, Ablett S, Martin DR et al (2003) Application of the NMR-MOUSE to food emulsions. J Magn Reson 165:49–58. https://doi.org/10.1016/S1090-7807(03)00243-X

Pereira FMV, Hashimoto JC, Pallone JAL, Colnago LA (2015) Determination of quality parameters for mustard sauces in sealed packets using time-domain nuclear magnetic resonance spectroscopy and chemometrics. Food Anal Methods 8:122–125. https://doi.org/10.1007/s12161-014-9877-8

Pereira FMV, Carvalho A de S, Cabeça LF, Colnago LA (2013) Classification of intact fresh plums according to sweetness using time-domain nuclear magnetic resonance and chemometrics. Microchem J 108:14–17. https://doi.org/10.1016/j.microc.2012.12.003

Perlo J, Casanova F, Blümich B (2005) Profiles with microscopic resolution by single-sided NMR. J Magn Reson 176:64–70. https://doi.org/10.1016/j.jmr.2005.05.017

Pinter MD, Harter T, McCarthy MJ, Augustine MP (2014) Towards using NMR to screen for spoiled tomatoes stored in 1,000 l, aseptically sealed, metal-lined totes. Sensors 14:4167–4176. https://doi.org/10.3390/s140304167

Prestes RA, Colnago LA, Forato LA et al (2007) A rapid and automated low resolution NMR method to analyze oil quality in intact oilseeds. Anal Chim Acta 596:325–329. https://doi.org/10.1016/j.aca.2007.06.022

Price HC, Mattsson J, Murray BJ (2016) Sucrose diffusion in aqueous solution. Phys Chem Chem Phys 18:19207–19216. https://doi.org/10.1039/c6cp03238a

Resende MT, Osheter T, Linder C, Wiesman Z (2021) Proton low field NMR relaxation time domain sensor for monitoring of oxidation stability of PUFA-Rich oils and emulsion products. Foods 10:1385. https://doi.org/10.3390/foods10061385

Ribeiro FZ, Marconcini LV, de Toledo IB et al (2010) Nuclear magnetic resonance water relaxation time changes in bananas during ripening: a new mechanism. J Sci Food Agric 90:2052–2057. https://doi.org/10.1002/jsfa.4051

Rodriguez-Saona LE, Allendorf ME (2011) Use of FTIR for rapid authentication and detection of adulteration of food. Annu Rev Food Sci Technol 2:467–483. https://doi.org/10.1146/annurev-food-022510-133750

Ronen I, Webb AG (2023) 1H NMR spectroscopy of strongly J-coupled alcohols acquired at 50 mT (2 MHz) using a Carr–Purcell–Meiboom–Gill echo technique. Pure Appl Chem 95:1067–1074. https://doi.org/10.1515/pac-2023-0102

Sadler G, Chappas W, Pierce DE (2001) Evaluation of e-beam, gamma- and X-ray treatment on the chemistry and safety of polymers used with pre-packaged irradiated foods: a review. Food Addit Contam 18:475–501. https://doi.org/10.1080/02652030119263

Santos PM, Colnago LA (2018) Comparison among MIR, NIR, and LF-NMR techniques for quality control of jam using chemometrics. Food Anal Methods 11:2029–2034. https://doi.org/10.1007/s12161-018-1195-0

Santos PM, Kock FVC, Santos MS et al (2017) Non-invasive detection of adulterated olive oil in full bottles using time-domain NMR relaxometry. J Braz Chem Soc 28:385–390. https://doi.org/10.5935/0103-5053.20160188

Singh K, Blümich B (2016) NMR spectroscopy with compact instruments. TrAC Trends Anal Chem 83:12–26. https://doi.org/10.1016/j.trac.2016.02.014

Sobieski DN, Mulvihill G, Broz JS, Augustine MP (2006) Towards rapid throughput NMR studies of full wine bottles. Solid State Nucl Magn Reson 29:191–198. https://doi.org/10.1016/j.ssnmr.2005.08.014

Solovyev PA, Fauhl-Hassek C, Riedl J et al (2021) NMR spectroscopy in wine authentication: an official control perspective. Compr Rev Food Sci Food Saf 20:2040–2062. https://doi.org/10.1111/1541-4337.12700

Song Y-Q (2009) A 2D NMR method to characterize granular structure of dairy products. Prog Nucl Magn Reson Spectrosc 55:324–334. https://doi.org/10.1016/j.pnmrs.2009.07.001

Stork H, Gädke A, Nestle N (2006) Single-sided and semisingle-sided NMR sensors for highly diffusive samples: application to bottled beverages. J Agric Food Chem 54:5247–5252. https://doi.org/10.1021/jf060431m

Tang F, Vasas M, Hatzakis E, Spyros A (2019) Magnetic resonance applications in food analysis. In: Annual Reports on NMR Spectroscopy. Academic Press Inc., pp 239–306. https://doi.org/10.1016/bs.arnmr.2019.04.005

Todt H, Guthausen G, Burk W et al (2006) Water/moisture and fat analysis by time-domain NMR. Food Chem 96:436–440. https://doi.org/10.1016/j.foodchem.2005.04.032

Trezza E, Haiduc AM, Goudappel GJW, van Duynhoven JPM (2006) Rapid phase-compositional assessment of lipid-based food products by time domain NMR. Magn Reson Chem 44:1023–1030. https://doi.org/10.1002/mrc.1893

Uguz SS, Ozel B, Grunin L et al (2022) Non-conventional time domain (TD)-NMR approaches for food quality: case of gelatin-based candies as a model food. Molecules 27:6745. https://doi.org/10.3390/molecules27196745

Utsuzawa S, Fukushima E (2017) Unilateral NMR with a barrel magnet. J Magn Reson 282:104–113. https://doi.org/10.1016/j.jmr.2017.07.006

van Duynhoven J, Voda A, Witek M, Van As H (2010) Chapter 3 - Time-domain NMR applied to food products. In: Annual reports on NMR spectroscopy. Academic Press, pp 145–197

Veliyulin E, Mastikhin IV, Marble AE, Balcom BJ (2008) Rapid determination of the fat content in packaged dairy products by unilateral NMR. J Sci Food Agric 88:2563–2567. https://doi.org/10.1002/jsfa.3391

Verbi Pereira FM, Rebellato AP, Lima Pallone JA, Colnago LA (2015) Through-package fat determination in commercial samples of mayonnaise and salad dressing using time-domain nuclear magnetic resonance spectroscopy and chemometrics. Food Control 48:62–66. https://doi.org/10.1016/j.foodcont.2014.02.028

Vigli G, Philippidis A, Spyros A, Dais P (2003) Classification of edible oils by employing 31P and 1H NMR spectroscopy in combination with multivariate statistical analysis. A proposal for the detection of seed oil adulteration in virgin Olive oils. J Agric Food Chem 51:5715–5722. https://doi.org/10.1021/jf030100z

Webb A, Najac C, Ronen I (2023) Rapid quantification of alcohol content in intact bottles of wine using scalar-coupled spectroscopy at low field. Appl Magn Reson 54:1321–1328. https://doi.org/10.1007/s00723-023-01585-0

Weekley AJ, Bruins P, Augustine MP (2002) Nondestructive method of determining acetic acid spoilage in an unopened bottle of wine. Am J Enol Vitic 53:318–321. https://doi.org/10.5344/ajev.2002.53.4.318

Weekley AJ, Bruins P, Sisto M, Augustine MP (2003) Using NMR to study full intact wine bottles. J Magn Reson 161:91–98. https://doi.org/10.1016/S1090-7807(02)00177-5

Wu X, Liang X, Wang Y et al (2022) Non-destructive techniques for the analysis and evaluation of meat quality and safety: a review. Foods 11:3713. https://doi.org/10.3390/foods11223713

Xu Z, Zhou X, Chen K (2024) An accurate method for the detection of pork fat content based on time-domain nuclear magnetic resonance. In: 2024 IEEE 6th Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC). pp 224–228

Zeng S, Li M, Li G et al (2022) Innovative applications, limitations and prospects of energy-carrying infrared radiation, microwave and radio frequency in agricultural products processing. Trends Food Sci Technol 121:76–92. https://doi.org/10.1016/j.tifs.2022.01.032

Zhang J, Bhatt T (2014) A guidance document on the best practices in food traceability. Compr Rev Food Sci Food Saf 13:1074–1103. https://doi.org/10.1111/1541-4337.12103

Zhang Y, Ma Z, Chen J et al (2024) Electromagnetic wave-based technology for ready-to-eat foods preservation: a review of applications, challenges and prospects. Crit Rev Food Sci Nutr. https://doi.org/10.1080/10408398.2024.2399294

Zhang Q, Huo Y, Yang Q et al (2025) Migration of chemical substances from packaging materials to food. Food Chem 485:144544. https://doi.org/10.1016/j.foodchem.2025.144544