

A Simple Overview in Magnetic Resonance Imaging Application in Evaluation of Food Quantity and Quality Aspects

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Abstract

Magnetic resonance imaging (MRI) has been a professional method in medical diagnostics for many years. Recently, considering the increase in population, preparing healthy food is a worldwide challenge. Hypothesis and implementation of MRI in research of food is approximately new. MRI is considered as a green, noninvasive, low cost, rapid, and nondestructive experimental method for investigating food processing. This method could be used in a short time while its results are suitable to apply in different industries even in online monitoring. Utilizing MRI techniques enhances the capacity to quantify basic processes such as gelation, crystallization, drying, dehydration, freezing, diffusion, and flow that occur in food products. This technology equips food scientists with a robust tool in the physicochemical properties study of food systems or specified food components and assessing them throughout diverse processes. This technique has some disadvantages in some process conditions too.

Keywords

Magnetic resonance imaging, Magnetization of materials, Image, Green method, Nondestructive analysis

Introduction

The increased demand for food is a significant challenge for global food security and some of the foods are more important because are categorized as staple foods [1]. Usually, politics about solving this problem is focused on improving grains like wheat using classic and molecular breeding techniques [1, 2], and enhancing the quality and durability of some food products. Usually, food is a combination of grains, fruits, vegetables, meats, and additives. Quality control of these complicated mixtures is difficult and needs a lot of time [3, 4].

Application of MRI technology holds immense potential in the food industry, during a short time [4, 5]. MRI usage could be qualitative and quantitative, but in different eras. Its usage in medical science is qualitative, contrary to its use in the food industry [6]. Food quantity usually has two aspects: physical properties (volume, surface, area, and porosity), and chemical properties (moisture content, oil content, and other basic compounds) [6-8].

MRI enables non-destructive and detailed analysis of food quality, composition, and safety parameters as well [9, 10]. By generating high-resolution images, MRI can detect internal defects, monitor moisture content, and assess structural integrity without altering the food's properties, even in opaque systems [3, 10-12]. This capability is invaluable for ensuring the safety and quality of food prod-

ucts throughout production, storage, and distribution processes [13]. As technology advances, MRI continues to play a pivotal role in enhancing food safety standards and ensuring consumer confidence in the global food supply chain [3, 14].

In a world dominated by MRI, which utilizes proton resonance, this non-invasive imaging technique holds sway primarily in medical diagnostics [15, 16]. Recently, MRI technology has expanded beyond traditional boundaries, penetrating various fields such as the intriguing realm of food science and technology [11, 12, 17, 18]. It now plays a pivotal role in exploring food systems, providing valuable insights into the physical and chemical properties of edibles, while ensuring the integrity of the sample [19]. The captivating ability of MRI to reveal detailed insights into the internal structure, composition, and dynamics of materials has sparked enthusiastic interest among scholars and industry experts, driving them towards new realms of innovation in food quality assessment, process optimization, and product development [8, 15, 20–24].

Samples can undergo multiple studies under consistent or modified conditions, providing notable benefits such as time efficiency, heightened accuracy, and more detailed interior surface analysis compared to preparative microscopy. In many cases, food systems require meticulous step-by-step construction from fundamental ingredients to complex systems to investigate the impacts of individual components and assess interactions between them. By comprehending the underlying processes deeply, it becomes economically viable to develop novel products or equipment with improved processing conditions during production [20, 25–29]. The limitation of using MRI is in the process that some part of food changes his physical property. For example, during drying, freezing, chilling, and freeze-drying process, monitoring by MRI has faced with challenge and because of phase changing in fats and water, the final data may be not exactly reliable [10, 12, 30].

Techniques of MRI expand our ability to measure fundamental processes taking place within food products, such as crystallization, dehydration, gelation, diffusion, and flow [31]. MRI enables non-disturbing measurements of mobility, saturation, and chemical species compositions. This includes studying phenomena like fat crystallization, emulsion stability, fruit maturation, freezing processes, fat content, and volumetric changes [32–35]. Recently, many researchers have studied process controlling with MRI in different fields: meat science, cereal science, fishing industry, fruits and vegetables storage, dairy industry [36–43].

Hypothesis of MRI

Basic principles of MRI

MRI methods utilize the magnetic properties of a material's protons, which arise from the interaction between the atomic particles of the material and a magnetic field that exist externally (Figure 1 and figure 2). Every proton possesses a magnetic moment, while are aligned in the same direction or in the opposite direction with the external magnetic field [44].

When protons are aligned in the same direction, they need lower free energy comparing opposite direction. Proton

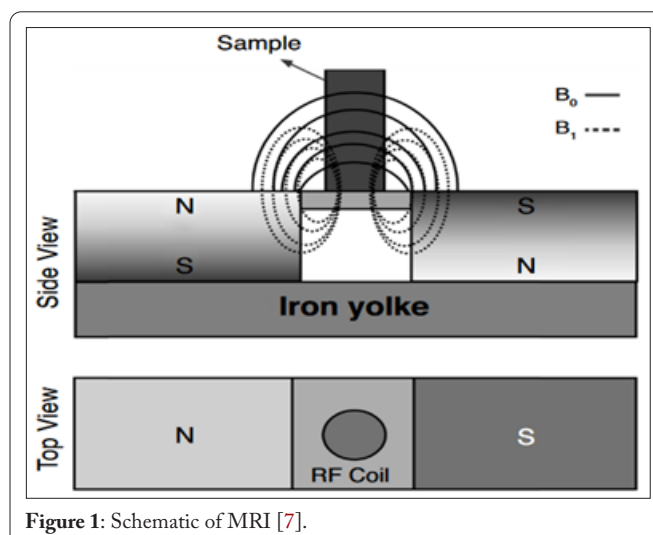


Figure 1: Schematic of MRI [7].

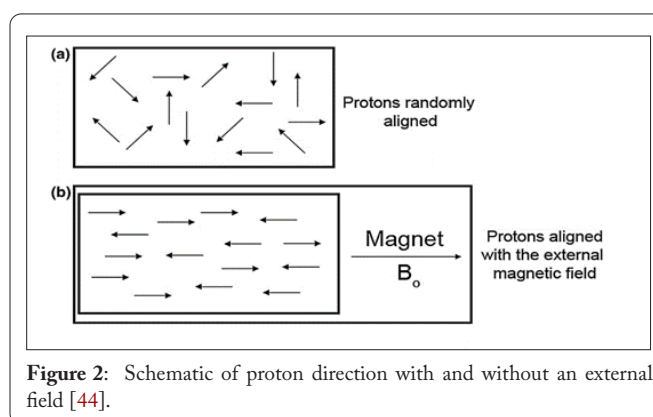


Figure 2: Schematic of proton direction with and without an external field [44].

numbers that are aligned in the same direction (B_0) are slightly higher than the ones that face the opposite direction (Figure 3) [44].

Nuclei that exhibit nuclear magnetic resonance (NMR) include ^1H , ^{31}P , ^{15}N , and ^{23}Na . Magnetic resonance techniques are specifically designed to estimate the macroscopic magnetization of a material sample. In a magnetic resonance experiment, information is gathered by placing a sample within a homogenous external field denoted as B_0 . The application of this field causes the nuclei exhibiting magnetic resonance to align and generate a small measurable magnetic moment. This induced magnetization is what makes MR techniques non-in-

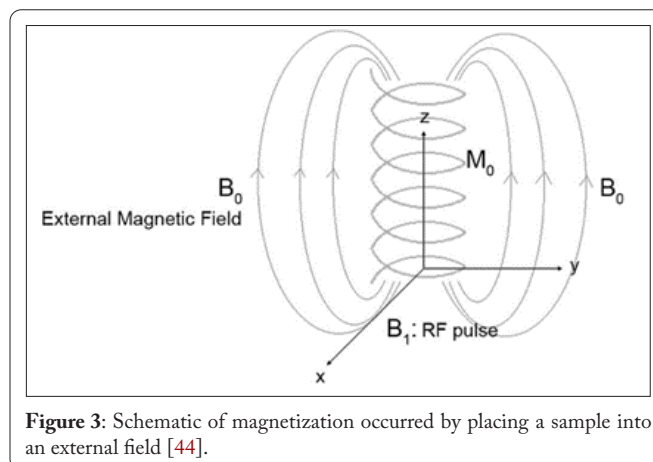


Figure 3: Schematic of magnetization occurred by placing a sample into an external field [44].

vasive. In many food research applications, a common spin-active nucleus resonates under specific conditions in the presence of a magnetic field. When an oscillating magnetic field at the correct frequency is applied, the nucleus resonates (precesses) about its equilibrium position. The frequency of the oscillating magnetic field required for resonance is known as the Larmor frequency ω_0 , defined by the Larmor equation (Equation 1):

$$\omega_0 = \gamma B_0 \quad 1$$

In which ω_0 represents the radio frequency (RF) in MHz, B_0 denotes the magnetic field strength in Tesla, and γ is the gyromagnetic ratio, a constant specific to each nucleus.

A secondary magnetic field (B_1) is applied as an RF pulse, causing the nuclei to transition into a non-equilibrium state. After this pulse, the excited nuclear spins release energy and return to the equilibrium state by precessing back to their original orientation at the Larmor frequency [20, 34, 45, 46].

The relaxation of magnetization towards the equilibrium state can be characterized by two relaxation time constants. Spin-lattice relaxation (T_1) entails the transfer of energy, often enthalpic, between the excited nuclear spins and their surrounding lattice. Spin-spin relaxation (T_2) involves the exchange of energy among similar nuclei and can be conceptualized as an entropic process [44, 47, 48]. Both time constants are essential in MRI experiments (Figure 4). Differences in relaxation times result in contrast in the NMR image and variations in both proton signal intensity and frequency within the localized spectrum [34].

Applications of MRI in the Evaluation of Internal Quality Factors in Food and Agricultural Products

MRI has proven to be a powerful method for evaluating internal quality aspects of food products (Figure 5). The assessment of agricultural and food product quality has been extensively studied using MRI [4, 15, 49–51].

Process control

Foods are dispersed multiphase systems (Suspensions, foams, emulsions, and porous solids) [52]. NMR has been widely advocated as a sensor for process control, owing to its exceptional specificity and capability to quantitatively assess internal properties. In the context of food systems, especially fresh fruits and vegetables, consumer purchase decisions are often influenced by external appearance. Nonetheless, internal quality holds utmost significance for consumption and production objectives [53].

NMR parameters are sensitive to plant issue's structure and compositions and different issues causes image changes in MRI. By MRI, it is not possible to obtain subcellular information, but does provide apparent relaxation parameters. Many times, in different fruit and vegetables textures, there are small spaces filled with gas, water or their combinations. Gas and water have different magnetic characteristics and combination of these features, causes irreversible signal loss during echo time [15].

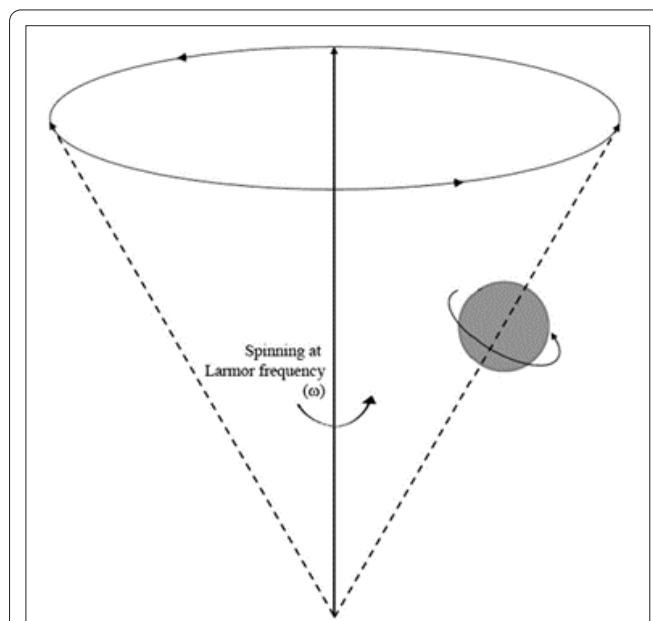


Figure 4: Schematic depicting the precessional motion of protons [44].

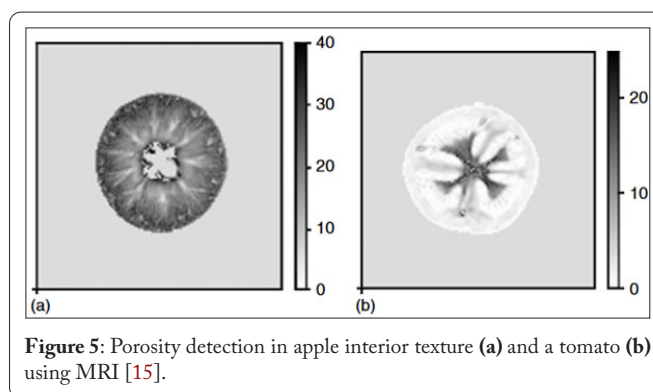


Figure 5: Porosity detection in apple interior texture (a) and a tomato (b) using MRI [15].

The dried fruit processor needs information on soluble solids content to predict the quality of the final product. In addition to the concentration of constituents in fruits or vegetables, various internal defects present challenges for detection using optical sensors. MRI is notably effective in identifying internal defects such as hollow heart in potatoes, brown center and bruises in apples, and freeze damage in oranges [53, 54]. Several research studies have focused on process control in fruits and vegetables, including issues like water core disease in apples [55], the mealiness in apple and peach [56, 57], core breakdown in pear [58, 59], dehydration of radishes, kiwi fruit, and strawberry [59–63].

Drying

Monitoring drying process with MRI has been done on various whole fresh agricultural products. However, due to their heightened morphological complexity, there have been no efforts to model the outcomes using diffusion equations. Significant research has been dedicated to optimizing drying parameters for beans. Key objectives for process enhancement include enhancing water intake rates and water-holding capacity, while minimizing starch matting and bean splitting [53, 64, 65].

Damage to beans, such as cracked seed coats, can lead to various issues including reduced yield, oxidation of lipids, canned products starching, and increased thermal requirements for canning. The processing quality of dried beans is typically evaluated through water content measurement [66, 67].

Rehydration

Many dried foods need to be rehydrated by consumers before consumption, underscoring the need to guarantee satisfactory quality in the rehydrated product. Rehydrated food quality depends on the freezing method, because it has considerable effect on ice crystal size, freezing rate, and porous structure. A thorough MRI investigation into the rehydration of spaghetti has been documented. In the case of spaghetti, factors like pastiness and unity after rehydration serve as main factor of quality, and rehydration should not be overly slow [68].

The spaghetti wheat used and the temperature during extrusion process are two main important factors. The extrusion process can involve durum wheat with hard texture and high gluten content, soft wheats, or these two mixtures, each choice affects significantly on the kinetics of rehydration. In raw materials choosing step, MRI can be useful for both optimizing the raw materials selection by providing detailed insights into the moisture profiles, considering the final spaghetti quality during rehydration and cooking time [68, 69, 70].

Freezing and freeze-thawing

Crystallization process consists of two steps: nucleation and the growth of the crystals. The nucleation stage has two sub-divisions: primary nucleation and secondary nucleation (when new crystals are formed in the presence of formerly created crystals) [31].

Freezing, whether through crystallization or amorphous crystals development, reduces mobility of molecules, thereby increasing relaxation rates and decreased the MR signal, with limited resolution [31]. There are some limitations in using MRI to evaluate freeze products. The contrast between fat and muscles is not considerable immediately after animal slaughter but increases during ripening because of drying muscles during time [15]. Besides, the environmental temperature can affect the final result of MRI. Fat usually starts crystallization under 4 °C and causes some errors in signals during echo time [15].

In the food samples always, there are movements of the freezing interface, including chicken, beef, meat, potatoes, peas, and corn [71]. Normally, food freezes in a vast range of temperatures, while each temperature below zero characterized by a specific ratio of liquid water to ice and may cause some damage to the animal or plant texture [72]. This phenomenon occurs because the biopolymers' surface changes the dynamic and structural state of adjacent molecules of water matrix, preventing them from forming a regular ice lattice. As a result, a portion of solution with water is still liquid even at temperatures lower than -150 °C [31]. Due to varying biopolymer and solute compositions, different subcellular organelles within cellular fruit and vegetable tissues display

unique freezing behaviors. For instance, starch granules and cell walls and starch granules in potatoes retain liquid water even at -25 °C. This inherent intricacy makes it challenging to predict the quantity of liquid water and ice present at temperatures below freezing, leading to uncertainty about the latent released during the freezing process [73, 74]. Different texture damages after freezing process, is not uniform and is completely depends on the method, temperature, and time of freezing. The issue damage causes less restriction of the water molecules that could be monitored by longer T2 relaxation and can be identified [31, 73, 75, 76]. By the way, the accurate segmentation of tissue into damaged and non-damaged regions by MRI comes with a challenge [73].

MRI plays a crucial role in elucidating the complicated freezing phenomenon by imaging the real-time of ice and liquid water spatial distribution. Ice has an extremely limited transverse relaxation time, it does not contribute significantly to the MRI signal, thereby allowing only the unfrozen water to affect image intensity. In the realm of food freezing, MRI data provides insights into the local ratio of liquid-to-solid water phases [77]. Accurate enthalpy data derived from MRI can only be reliably obtained when the system is in equilibrium. In situations where the system is in a metastable state, such as being subcooled, the enthalpy estimated from MR data may be inaccurate. Different experiments have shown that temperature changes greater than 3 °C can lead to errors in the final results. Preparing samples with a size of 2.5 mm could solve this problem [78]. Non-invasive and continuous monitoring of the freezing process using MRI has already been investigated across a variety of food types, including orange juice, beef, carrots, chicken, corn, dough, berries, potatoes, fish, and baked products [75, 79, 80].

Food rheology

MRI offers unique advantages in flow studies of suspensions that are concentrated or colloidal and other cloudy liquids where optical methods like laser doppler anemometry or visual inspection of moving particles is impossible. Integrating flow imaging sequences with pulse sequences to NMR parameters like relaxation time, diffusion coefficients, or chemical shifts offers the theoretical possibility to simultaneously map velocity alongside other parameters such as concentration, temperature, or reaction rate [7, 81].

The flow feature is one of the most important characteristics in granules or fluid food products. Usually, it has non-Newtonian nature and is important for designing and optimizing the quality and sensory properties of foods, besides their efficient processability [82].

Several MRI flow techniques enable non-invasive observation of velocity profiles and residence times during completely protected processes, for instance, aseptic, and extrusion. MRI techniques useful for determining velocities and residence times generally fall into two categories: time-of-flight (ToF) and velocity-encoded techniques. Presently, ToF techniques have received more attention in food science journals and are more accessible for non-physicists to understand [34, 83, 84].

Evaluation quality and quantity of some plant products like fruits, seeds, cereals, tubers, and vegetables is very difficult and for transformation in food processing and shelf-life studies, MRI is a suitable technique because of its possibility in quantitative assessment of water and oil migration [82].

Crystallization and melting phenomena

MRI has facilitated direct monitoring of the crystallization kinetics of fats in bulk or in fat/water emulsions containing various triglyceride species [53, 54]. Integrating MRI data with calorimetric studies can effectively test the assumption of local equilibria in calculations of freezing rates and help estimate potential errors under different freezing conditions [85–87]. MRI has been utilized to study the liquefy and oiling-off processes in cheddar cheeses, encompassing both classic and low-fat varieties. Usually, fat and water crystals in under-tempered products could not form uniform as well-tempered ones. In some foods that mostly contain low saturated triacylglycerols, crystals form a crystalline microstructure between the center and outer part of product. During storage, because of migration of low saturated triacylglycerol, the concentration changes. In this period, crystals tend to form in the outer layer of food. By the way, MRI monitoring is a helpful technique in quality evaluation [88–91].

Conclusions

MRI is an expanding field with significant potential to address questions and enhance understanding in food science and processing beyond what traditional techniques can achieve. MRI provides a versatile, noninvasive, nondestructive, and green method of experimental approach for studying various aspects of food processing. This discussion has covered MRI applications in food science including freezing and crystallization, diffusion, emulsions, drying, syneresis, and flow.

One limitation of using MRI is its inability to resolve sub-cellular information. In complex natural foods, various parts within intercellular spaces and plant textures induce irreversible signal loss during echo time, leading to testing errors.

In animal textures, this technique faces different challenges, particularly related to the test environment temperature. Images can be inaccurate at temperatures below 4 °C because the fat in carcasses partially crystallizes, resulting in low signals. MRI monitoring during the freezing process has shown varying results, as the images differed with temperature changes exceeding 3 °C. Recently, researchers have reported that reducing the sample size could solve this problem.

During the freezing process, many parts of plant or animal textures can be damaged, and distinguishing between damaged and undamaged parts is impossible with MRI monitoring. This technique has limited resolution and sensitivity but is very fast and needs very little sample preparation.

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None.

Conflict of Interest

None.

References

1. Rizi MS, Mohammadi M. 2023. Breeding crops for enhanced roots to mitigate against climate change without compromising yield. *Rhizosphere* 26: 100702. <https://doi.org/10.1016/j.rhisph.2023.100702>
2. Shaltouki-Rizi M, Smith NE, Brown-Guedira G, Mohammadi M. 2024. Shared quantitative trait loci underlying root biomass and phenology in wheat (*Triticum aestivum* L.). *J Agron Crop Sci* 210(3): 1–15. <https://doi.org/10.1111/jac.12700>
3. Van As H, Van Duynhoven J. 2013. MRI of plants and foods. *J Magn Reson* 229: 25–34. <https://doi.org/10.1016/j.jmr.2012.12.019>
4. 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 Bioproc Tech* 12: 1435–1451. <https://doi.org/10.1007/s11947-019-02296-w>
5. Patel KK, Khan MA, Kar A. 2015. Recent developments in applications of MRI techniques for foods and agricultural produce—an overview. *J Food Sci Technol* 52: 1–26. <https://doi.org/10.1007/s13197-012-0917-3>
6. Caballero D, Caro A, del Mar Avila M, Rodriguez PG, Antequera T, et al. 2017. New fractal features and data mining to determine food quality based on MRI. *IEEE Lat Am Trans* 15(9): 1777–1784. <https://doi.org/10.1109/TLA.2017.8015085>
7. 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>
8. Schork N, Schuhmann S, Gruschke O, Gross D, Zick K, et al. 2020. Recent MRI and diffusion studies of food structures. *Annu Rep NMR Spectrosc* 100: 203–264. <https://doi.org/10.1016/bs.arnmr.2020.02.002>
9. Gowen AA, Tiwari BK, Cullen PJ, McDonnell K, O'donnell CP. 2010. Applications of thermal imaging in food quality and safety assessment. *Trends Food Sci Technol* 21(4): 190–200. <https://doi.org/10.1016/j.tifs.2009.12.002>
10. Belton PS, Gil AM, Webb GA, Rutledge D, Mariette F. 2003. NMR Relaxometry and MRI for Food Quality Control: Application to Dairy Products and Processes. In Belton PS, Gil AM, Webb GA, Rutledge D (eds) *Magnetic Resonance in Food Science—Latest Developments*, pp 209–222.
11. Koizumi M, Naito S, Ishida N, Haishi T, Kano H. 2008. A dedicated MRI for food science and agriculture. *Food Sci Technol Res* 14(1): 74–82. <https://doi.org/10.3136/fstr.14.74>
12. Jha SN. 2010. *Nondestructive Evaluation of Food Quality: Theory and Practice*. In Jha SN (ed) Springer Science and Business Media. Springer Berlin, Heidelberg, pp 288–299.
13. Antequera T, Caballero D, Grassi S, Uttaro B, Perez-Palacios T. 2021. Evaluation of fresh meat quality by hyperspectral imaging (HSI), nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI): a review. *Meat Sci* 172: 108340. <https://doi.org/10.1016/j.meatsci.2020.108340>
14. Sanchez PD, Arogancia HB, Boyles KM, Pontillo AJ, Ali MM. 2022. Emerging nondestructive techniques for the quality and safety evaluation of pork and beef: recent advances, challenges, and future perspectives. *Appl Food Res* 2(2): 100147. <https://doi.org/10.1016/j.afres.2022.100147>
15. Mariette F, Collewet G, Davenel A, Lucas T, Musse M. 2012. Quantitative MRI in food science & food engineering. *Encyclopedia Mag Res* 1(1): 205–214. <https://doi.org/10.1002/9780470034590.emrstm1272>
16. Sechi E, Cacciaguerra L, Chen JJ, Mariotto S, Fadda G, et al. 2022. Myelin oligodendrocyte glycoprotein antibody-associated disease (MOGAD): a review of clinical and MRI features, diagnosis, and management. *Front Neurol* 13: 1–21. <https://doi.org/10.3389/fneur.2022.885218>

17. Thybo AK, Szczypiński PM, Karlsson AH, Dønstrup S, Stødkilde-Jørgensen HS, et al. 2004. Prediction of sensory texture quality attributes of cooked potatoes by NMR-imaging (MRI) of raw potatoes in combination with different image analysis methods. *J Food Eng* 61(1): 91-100. [https://doi.org/10.1016/S0260-8774\(03\)00190-0](https://doi.org/10.1016/S0260-8774(03)00190-0)
18. Li M, Li B, Zhang W. 2018. Rapid and non-invasive detection and imaging of the hydrocolloid-injected prawns with low-field NMR and MRI. *Food Chem* 242: 16-21. <https://doi.org/10.1016/j.foodchem.2017.08.086>
19. Liu Y, Sun Q, Wei S, Xia Q, Pan Y, et al. 2022. LF-NMR as a tool for predicting the 3D printability of surimi-starch systems. *Food Chem* 374: 131727. <https://doi.org/10.1016/j.foodchem.2021.131727>
20. Ates EG, Domenici V, Florek-Wojciechowska M, Gradišek A, Kruk D, et al. 2021. Field-dependent NMR relaxometry for food science: applications and perspectives. *Trends Food Sci Technol* 110: 513-524. <https://doi.org/10.1016/j.tifs.2021.02.026>
21. Luo H, Guo C, Lin L, Si Y, Gao X, et al. 2020. Combined use of rheology, LF-NMR, and MRI for characterizing the gel properties of hairtail surimi with potato starch. *Food Bioproc Tech* 13: 637-647. <https://doi.org/10.1007/s11947-020-02423-y>
22. Yang D, Wu G, Li P, Qi X, Zhang H, et al. 2020. The effect of fatty acid composition on the oil absorption behavior and surface morphology of fried potato sticks via LF-NMR, MRI, and SEM. *Food Chem* 7: 100095. <https://doi.org/10.1016/j.fochx.2020.100095>
23. Cao R, Liu X, Liu Y, Zhai X, Cao T, et al. 2021. Applications of nuclear magnetic resonance spectroscopy to the evaluation of complex food constituents. *Food Chem* 342: 128258. <https://doi.org/10.1016/j.foodchem.2020.128258>
24. Ozel B, Oztop MH. 2021. A quick look to the use of time domain nuclear magnetic resonance relaxometry and magnetic resonance imaging for food quality applications. *Curr Opin Food Sci* 41: 122-129. <https://doi.org/10.1016/j.cofs.2021.03.012>
25. Fraga-Corral M, Carpena M, Garcia-Oliveira P, Pereira AG, Prieto MA, et al. 2022. Analytical metabolomics and applications in health, environmental and food science. *Crit Rev Anal Chem* 52(4): 712-734. <https://doi.org/10.1080/10408347.2020.1823811>
26. Utpott M, Rodrigues E, de Oliveira RA, Mercali GD, Flôres SH. 2022. Metabolomics: an analytical technique for food processing evaluation. *Food Chem* 366: 130685. <https://doi.org/10.1016/j.foodchem.2021.130685>
27. Milani MI, Rossini EL, Catelani TA, Pezza L, Toci AT, et al. 2020. Authentication of roasted and ground coffee samples containing multiple adulterants using NMR and a chemometric approach. *Food Control* 112: 107104. <https://doi.org/10.1016/j.foodcont.2020.107104>
28. Smeets PA, Deng R, Van Eijnatten EJ, Mayar M. 2021. Monitoring food digestion with magnetic resonance techniques. *Proc Nutr Soc* 80(2): 148-158. <https://doi.org/10.1017/s0029665120007867>
29. Aganovic K, Hertel C, Vogel RF, John R, Schlüter O, et al. 2021. Aspects of high hydrostatic pressure food processing: perspectives on technology and food safety. *Compr Rev Food Sci Food Saf* 20(4): 3225-3266. <https://doi.org/10.1111/1541-4337.12763>
30. Bows JR, Patrick ML, Nott KP, Hall LD. 2001. Three-dimensional MRI mapping of minimum temperatures achieved in microwave and conventional food processing. *Int J Food Sci Technol* 36(3): 243-252. <https://doi.org/10.1046/j.1365-2621.2001.00444.x>
31. Parandi E, Pero M, Kiani H. 2022. Phase change and crystallization behavior of water in biological systems and innovative freezing processes and methods for evaluating crystallization. *Discov Food* 2(1): 1-6. <https://doi.org/10.1007/s44187-021-00004-2>
32. Zhang H, Zhang S, Chen Y, Luo W, Huang Y, et al. 2020. Non-destructive determination of fat and moisture contents in Salmon (*Salmo salar*) fillets using near-infrared hyperspectral imaging coupled with spectral and textural features. *J Food Compos Anal* 92: 103567. <https://doi.org/10.1016/j.jfca.2020.103567>
33. Liu YY, Liu Y, Wang XY, Jin YG. 2020. Changes in structure and flavor of egg yolk gel induced by lipid migration under heating. *Food Hydrocoll* 98: 105257. <https://doi.org/10.1016/j.foodhyd.2019.105257>
34. McCarthy MJ. 2012. Magnetic Resonance Imaging in Foods. In Springer Science & Business Media. Springer New York, pp 10-110.
35. Ebrahimnejad H, Ebrahimnejad H, Salajegheh A, Barghi H. 2018. Use of magnetic resonance imaging in food quality control: a review. *J Biomed Phys Eng* 8(1): 127.
36. Anedda R, Melis R, Curti E. 2021. Quality control in fiore sardo PDO cheese: detection of heat treatment application and production chain by MRI relaxometry and image analysis. *Dairy* 2(2): 270-287. <https://doi.org/10.3390/dairy2020023>
37. Cóccola ME, Basán N, Méndez CA, Dondo RG. 2022. Optimization of resource flows across the whole supply chain. Application to a case study in the dairy industry. *Comput Chem Eng* 158: 107632. <https://doi.org/10.1016/j.compchemeng.2021.107632>
38. Tang T, Zhang M, Mujumdar AS. 2022. Intelligent detection for fresh-cut fruit and vegetable processing: imaging technology. *Compr Rev Food Sci Food Saf* 21(6): 5171-5198. <https://doi.org/10.1111/1541-4337.13039>
39. Sand IK, Fitzgerald KC, Gu Y, Brandstadter R, Riley CS, et al. 2021. Dietary factors and MRI metrics in early multiple sclerosis. *Mult Scler Relat Dis* 53: 103031. <https://doi.org/10.1016/j.msard.2021.103031>
40. Anderssen KE, Syed S, Stormo SK. 2021. Quantification and mapping of tissue damage from freezing in cod by magnetic resonance imaging. *Food Control* 123: 107734. <https://doi.org/10.1016/j.foodcont.2020.107734>
41. Song P, Wang Z, Song P, Yue X, Bai Y, et al. 2021. Evaluating the effect of aging process on the physicochemical characteristics of rice seeds by low field nuclear magnetic resonance and its imaging technique. *J Cereal Sci* 99: 103190. <https://doi.org/10.1016/j.jcs.2021.103190>
42. Liu L, Hu X, Zou L. 2023. Wheat polysaccharides and gluten effect on water migration and structure in noodle doughs: an ¹H LF-NMR study. *J Cereal Sci* 110: 103628. <https://doi.org/10.1016/j.jcs.2023.103628>
43. Caballero D, Pérez-Palacios T, Caro A, Antequera T. 2023. Use of magnetic resonance imaging to analyse meat and meat products non-destructively. *Food Rev Int* 39(1): 424-440. <https://doi.org/10.1080/87559129.2021.1912085>
44. Kirtil E, Oztop MH. 2016. ¹H nuclear magnetic resonance relaxometry and magnetic resonance imaging and applications in food science and processing. *Food Eng Rev* 8: 1-22. <https://doi.org/10.1007/s12393-015-9118-y>
45. Hatzakis E. 2019. Nuclear magnetic resonance (NMR) spectroscopy in food science: a comprehensive review. *Compr Rev Food Sci Food Saf* 18(1): 189-220. <https://doi.org/10.1111/1541-4337.12408>
46. McCarthy MJ. 2011. Introduction to Magnetic Resonance Imaging (MRI). In Magnetic Resonance Imaging in Foods. Springer, Boston, pp 1-29.
47. De Deene Y. 2020. NMR and MRI of Gels. Royal Society of Chemistry.
48. Zhao M. 2016. Magnetic resonance mediated radio frequency coagulation for vascular repair. Doctoral dissertation, University of Massachusetts Lowell.
49. Ali MM, Hashim N, Abd Aziz S, Lasekan O. 2020. Principles and recent advances in electronic nose for quality inspection of agricultural and food products. *Trends Food Sci Technol* 99: 1-10. <https://doi.org/10.1016/j.tifs.2020.02.028>
50. Sanchez PD, Hashim N, Shamsudin R, Nor MZ. 2020. Applications of imaging and spectroscopy techniques for non-destructive quality evaluation of potatoes and sweet potatoes: a review. *Trends Food Sci Technol* 96: 208-221. <https://doi.org/10.1016/j.tifs.2019.12.027>
51. Brosnan T, Sun DW. 2004. Improving quality inspection of food products by computer vision—a review. *J Food Eng* 61(1): 3-16. [https://doi.org/10.1016/S0260-8774\(03\)00183-3](https://doi.org/10.1016/S0260-8774(03)00183-3)

52. Götz J. 2006. MRI in Food Process Engineering. In Webb GA (ed) Modern Magnetic Resonance. Dordrecht: Springer Netherlands, pp 1813-1818.
53. Kamal T, Cheng S, Khan IA, Nawab K, Zhang T, et al. 2019. Potential uses of LF-NMR and MRI in the study of water dynamics and quality measurement of fruits and vegetables. *J Food Process Preserv* 43(11): e14202. <https://doi.org/10.1111/jfpp.14202>
54. Srivastava RK, Talluri S, Beebi SK, Rajesh Kumar B. 2018. Magnetic resonance imaging for quality evaluation of fruits: a review. *Food Anal Methods* 11: 2943-2960. <https://doi.org/10.1007/s12161-018-1262-6>
55. Herremans E, Melado-Herreros A, Defraeye T, Verlinden B, Hertog M, et al. 2014. Comparison of X-ray CT and MRI of watercore disorder of different apple cultivars. *Postharvest Biol Technol* 87: 42-50. <https://doi.org/10.1016/j.postharvbio.2013.08.008>
56. Arefi A, Moghaddam PA, Mollazade K, Hassanpour A, Valero C, et al. 2015. Mealiness detection in agricultural crops: destructive and nondestructive tests: a review. *Compr Rev Food Sci Food Saf* 14(5): 657-680. <https://doi.org/10.1111/1541-4337.12152>
57. Barreiro P, Ortiz C, Ruiz-Altisent M, Ruiz-Cabello J, Fernández-Valle ME, et al. 2000. Mealiness assessment in apples and peaches using MRI techniques. *Magn Reson Imaging* 18(9): 1175-1181. [https://doi.org/10.1016/S0730-725X\(00\)00179-X](https://doi.org/10.1016/S0730-725X(00)00179-X)
58. Joseph M, Van Cauteren H, Postelmans A, Nugraha B, Verreydt C, et al. 2023. Porosity quantification in pear fruit with X-ray CT and spatially resolved spectroscopy. *Postharvest Biol Technol* 204: 112455. <https://doi.org/10.1016/j.postharvbio.2023.112455>
59. Lammertyn J, Dresselaers T, Van Hecke P, Jancsó P, Wevers M, et al. 2003. MRI and X-ray CT study of spatial distribution of core breakdown in 'conference' pears. *Magn Reson Imaging* 21(7): 805-815. [https://doi.org/10.1016/S0730-725X\(03\)00105-X](https://doi.org/10.1016/S0730-725X(03)00105-X)
60. Santagapita P, Laghi L, Panarese V, Tylewicz U, Rocculi P, et al. 2013. Modification of transverse NMR relaxation times and water diffusion coefficients of kiwifruit pericarp tissue subjected to osmotic dehydration. *Food Bioproc Tech* 6: 1434-1443. <https://doi.org/10.1007/s11947-012-0818-5>
61. Panarese V, Laghi L, Pisi A, Tylewicz U, Rosa MD, et al. 2012. Effect of osmotic dehydration on *Actinidia deliciosa* kiwifruit: a combined NMR and ultrastructural study. *Food Chem* 132(4): 1706-1712. <https://doi.org/10.1016/j.foodchem.2011.06.038>
62. Sun X, Hu J, Xiao H, Liu C, Yang F, et al. 2024. Effect of pectin addition on the drying characteristics of freeze-dried restructured strawberry blocks. *LWT* 192: 115716. <https://doi.org/10.1016/j.lwt.2023.115716>
63. Suchanek M, Olejniczak Z. 2020. Evaluation of osmotic dehydration process in plant tissue with low-field magnetic resonance imaging enhanced with paramagnetic ions. *Processes* 8(8): 887. <https://doi.org/10.3390/pr8080887>
64. Mikac U, Sepe A, Serša I. 2015. MR microscopy for noninvasive detection of water distribution during soaking and cooking in the common bean. *Magn Reson Imaging* 33(3): 336-345. <https://doi.org/10.1016/j.mri.2014.12.001>
65. Li P, Li Y, Wang L, Zhang H, Qi X, et al. 2020. Study on water absorption kinetics of black beans during soaking. *J Food Eng* 283: 110030. <https://doi.org/10.1016/j.jfoodeng.2020.110030>
66. Zhang L, McCarthy MJ. 2013. NMR study of hydration of navy bean during cooking. *LWT Food Sci Tech* 53(2): 402-408. <https://doi.org/10.1016/j.lwt.2013.03.011>
67. Divya S, Thyagarajan D, Sujatha G. 2013. Magnetic resonance imaging technology for process control and quality maintenance in food quality operation. *Int J Eng Technol* 4(6): 441-449.
68. Ogawa T, Adachi S. 2014. Measurement of moisture profiles in pasta during rehydration based on image processing. *Food Bioproc Tech* 7: 1465-1471. <https://doi.org/10.1007/s11947-013-1156-y>
69. Ogawa T. 2023. Elucidation of the mechanism by which the internal structure of food controls the quality. *Biosci Biotechnol Biochem* 87(9): 935-945. <https://doi.org/10.1093/bbb/zbab088>
70. Nguyen TK, Khalloufi S, Mondor M, Ratti C. 2020. Moisture profile analysis of food models undergoing glass transition during air-drying. *J Food Eng* 281: 109995. <https://doi.org/10.1016/j.jfoodeng.2020.109995>
71. Dalvi-Isfahan M, Jha PK, Tavakoli J, Daraei-Garmakhany A, Xanthakis E, et al. 2019. Review on identification, underlying mechanisms and evaluation of freezing damage. *J Food Eng* 255: 50-60. <https://doi.org/10.1016/j.jfoodeng.2019.03.011>
72. Shi Y, Zhang L, Ma W, Yang C, Han D, et al. 2022. Investigating unfrozen water and its components during freeze-thaw action in loess using a novel NMR technique. *Eur J Soil Sci* 73(4): e13262. <https://doi.org/10.1111/ejss.13262>
73. Hills BP, Goncalves O, Harrison M, Godward J. 1997. Real time investigation of the freezing of raw potato by NMR microimaging. *Magn Reson Chem* 35: 529-536. [https://doi.org/10.1002/\(SICI\)1097-458X\(199712\)35:13<S29::AID-OMR175>3.0.CO;2-K](https://doi.org/10.1002/(SICI)1097-458X(199712)35:13<S29::AID-OMR175>3.0.CO;2-K)
74. Zhang T, Zhao R, Liu W, Liu Q, Zhang L, et al. 2022. Dynamic changes of potato characteristics during traditional freeze-thaw dehydration processing. *Food Chem* 389: 133069. <https://doi.org/10.1016/j.foodchem.2022.133069>
75. Wang XY, Xie J, Chen XJ. 2021. Applications of non-invasive and novel methods of low-field nuclear magnetic resonance and magnetic resonance imaging in aquatic products. *Front Nutr* 8: 651804. <https://doi.org/10.3389/fnut.2021.651804>
76. Kaur M, Kumar M. 2020. An innovation in magnetic field assisted freezing of perishable fruits and vegetables: a review. *Food Rev Int* 36(8): 761-780. <https://doi.org/10.1080/87559129.2019.1683746>
77. Overduin CG, Fütterer JJ, Scheenen TW. 2016. 3D MR thermometry of frozen tissue: feasibility and accuracy during cryoablation at 3T. *J Magn Reson Imaging* 44(6): 1572-1579. <https://doi.org/10.1002/jmri.25301>
78. Hankiewicz JH, Celinski Z, Camley RE. 2021. Measurement of sub-zero temperatures in MRI using T1 temperature sensitive soft silicone materials: applications for MRI-guided cryosurgery. *Med Phys* 48(11): 6844-6858. <https://doi.org/10.1002/mp.15252>
79. Chen C, Zhang A, Cai Z, Sun J, Xu LX. 2011. Design of microprobe for accurate thermal treatment of tumor. *Cryo Letters* 32(3): 275-286.
80. Boguszyńska J, Rachocki A, Tritt-Goc J. 2005. Melting behavior of water confined in nanopores of white cement studies by ¹H NMR cryoporometry: effect of antifreeze additive and temperature. *Appl Magn Reson* 29(4): 639-653. <https://doi.org/10.1007/BF03166340>
81. Hauser JA, Muthurangu V, Steeden JA, Taylor AM, Jones A. 2016. Comprehensive assessment of the global and regional vascular responses to food ingestion in humans using novel rapid MRI. *Am J Physiol Regul Integr Comp Physiol* 310(6): R541-R545. <https://doi.org/10.1152/ajpregu.00454.2015>
82. Serial MR, Terenzi C, van Duynhoven J, Van As H. 2022. MRI of Transport and Flow in Plants and Foods. In Haber-Pohlmeier S, Blümich B, Ciobanu L (eds) Magnetic Resonance Microscopy: Instrumentation and Applications in Engineering, Life Science, and Energy Research. Wiley Online Library, pp 237-261.
83. Bölükçaya Z. 2022. Design of a continuous flow magnetic resonance system for rheological characterization. Master's Thesis, Middle East Technical University.
84. d'Avila MA, Powell RL, Phillips RJ, Shapley NC, Walton JH, et al. 2005. Magnetic resonance imaging (MRI): a technique to study flow and microstructure of concentrated emulsions. *Braz J Chem Eng* 22: 49-60. <https://doi.org/10.1590/S0104-66322005000100006>
85. Torregrossa F, Cinquanta L, Albanese D, Cuomo F, Librici C, et al. 2024. Vegan and sugar-substituted chocolates: assessing physicochemical characteristics by NMR relaxometry, rheology, and DSC. *Eur Food*

- Res Technol* 250(4): 1219-1228. <https://doi.org/10.1007/s00217-023-04457-w>
86. Kaur P, Singh M, Birwal P. 2021. Differential Scanning Calorimetry (DSC) for the Measurement of Food Thermal Characteristics and its Relation to Composition and Structure. In Khan MS, Rahman MS (eds) *Techniques to Measure Food Safety and Quality: Microbial, Chemical, and Sensory*. Springer, pp 283-328.
87. Mahato S, Zhu Z, Sun DW. 2019. Glass transitions as affected by food compositions and by conventional and novel freezing technologies: a review. *Trends Food Sci Technol* 94: 1-11. <https://doi.org/10.1016/j.tifs.2019.09.010>
88. Price KM. 2007. *Microstructure and functionality of processed cheese: the role of milk fat*. University Libraries.
89. Mehta BM. 2018. *Microstructure of Cheese Products*. In El-Bakry MMAR, Sanchez A, Mehta BM (eds) *Microstructure of Dairy Products*. Wiley Online Library, pp 145-179.
90. Ong L, Li X, Ong A, Gras SL. 2022. New insights into cheese microstructure. *Annu Rev Food Sci Technol* 13(1): 89-115. <https://doi.org/10.1146/annurev-food-032519-051812>
91. Simoneau C, McCarthy MJ, German JB. 1993. Magnetic resonance imaging and spectroscopy for food systems. *Food Res Int* 26(5): 387-398. [https://doi.org/10.1016/0963-9969\(93\)90082-T](https://doi.org/10.1016/0963-9969(93)90082-T)