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APPLICATION OF LOW-FIELD NUCLEAR MAGNETIC RESONANCE (LF-NMR) AND MAGNETIC RESONANCE IMAGING (MRI) IN FOOD ANALYSIS

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ABSTRACT

NMR/MRI spectroscopy is a reliable approach for analyzing mixtures at the molecular level without the need for separation or purification, making it excellent for food science applications. With the recent breakthroughs in the field, low-field nuclear magnetic resonance (LF- NMR) and magnetic resonance imaging (MRI) have shown to be fast, reliable and aids in non-invasive characterization of foods, which makes it an alternative to the laborious conventional techniques. The application of this novel technique has been explored by food scientists and continue to make advances in it's extensive application for food analysis and processing. This review focused on current applications of LF-NMR/MRI in food research precisely in quality control, food processing, food authentication, 3D printability and food packaging. Limitations as well as future prospects in LF-NMR/MRI applications were briefly discussed.

Keywords: Online low field nuclear magnetic resonance (LF-NMR), magnetic resonance imaging (MRI), food, food science, analysis

1. INTRODUCTION

In recent times, the demand for safe and quality processed foods has inspired the search for advanced technologies in food science owing to the flaws of the conventional technologies with respect to their robustness, sensitivity, cost-effectiveness, timeliness and selectivity. Consumers' choice and acceptability of food products are highly affected by the organoleptic features of food products such as nutritional traits, color, freshness, aroma, texture and flavor. As a result, improvement in the quality of food such as nutritional value, time limit, process cost minimization and safety has always been a primary in most food processing technologies (Erikson et al., 2012; Lund, 2003). Food scientists and nutritionists need robust and nondestructive analytical methods that can effectively analyze the composition and measure the physicochemical properties and functionality of food matrices. This will help the development and production of high quality and safe foods, as well as the design of nutrition-based approaches that promotes good health. It is a challenge achieving the parameters used in evaluating sensory attributes using the conventional methods. These methods do not only take longer time, but also reduce the overall product quality. Similarly, analyzing food quality using offline analytical techniques involves a series of processes, thus rendering it tedious and time- consuming (Marcone et al., 2013; Y. Zhang et al., 2018). In order to overcome these challenges, alternative techniques such as NIR, Gas chromatography and Raman spectroscopy are used in food quality analysis, depending greatly on online instrumentation. However, these techniques also come with their own limitations in food process control monitoring. In the case of near infrared (NIR), it is not sufficiently steady, reliable and requires the development of multivariate calibration models against a suitable reference method to be established mostly for online application (J. H. Cheng et al., 2013; Huang et al., 2008). Raman spectroscopy is costly and non-stable in its application in process analysis (J. H. Cheng et al., 2013; Jin et al., 2016; Yang & Ying, 2011). Gas chromatography has the limitation of being time-consuming and above all being non-invasive (Dalitz et al., 2012).

Nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI)-based sensors have been utilized in the medical field for tissue analysis. The high cost of these systems especially magnetic resonance (MR) imaging instruments limits their use in food research and industrial production. However, continuous advances in the field have made it possible to use NMR/MRI systems for food quality control applications both in industrial and research scales (Ezeanaka et al., 1947). Nuclear magnetic resonance (NMR) is a physical phenomenon that uses the magnetic properties of certain nuclei to provide detailed structural, dynamic and energy information of molecular compounds. NMR analysis is nondestructive, reproducible and highly accurate which offers a great opportunity to advance the field of food science. NMR is grouped into two: low-resolution nuclear magnetic resonance (LF-NMR) and high-resolution nuclear magnetic resonance (HF-NMR), with LF-NMR being dependent mainly on the NMR spectrum and MRI technique (Y. Zhang et al., 2018). High-field NMR instruments encompass superconducting magnets (200–750 MHz), which are not only expensive but also can be complex and signals obtained are difficult to analyze (Nordon et al., 2001). This had led to a growing interest in recent years for the use of low field (LF) owing to its distinctive characteristics of being portable, less costly and ability to detect adulterations in foods.

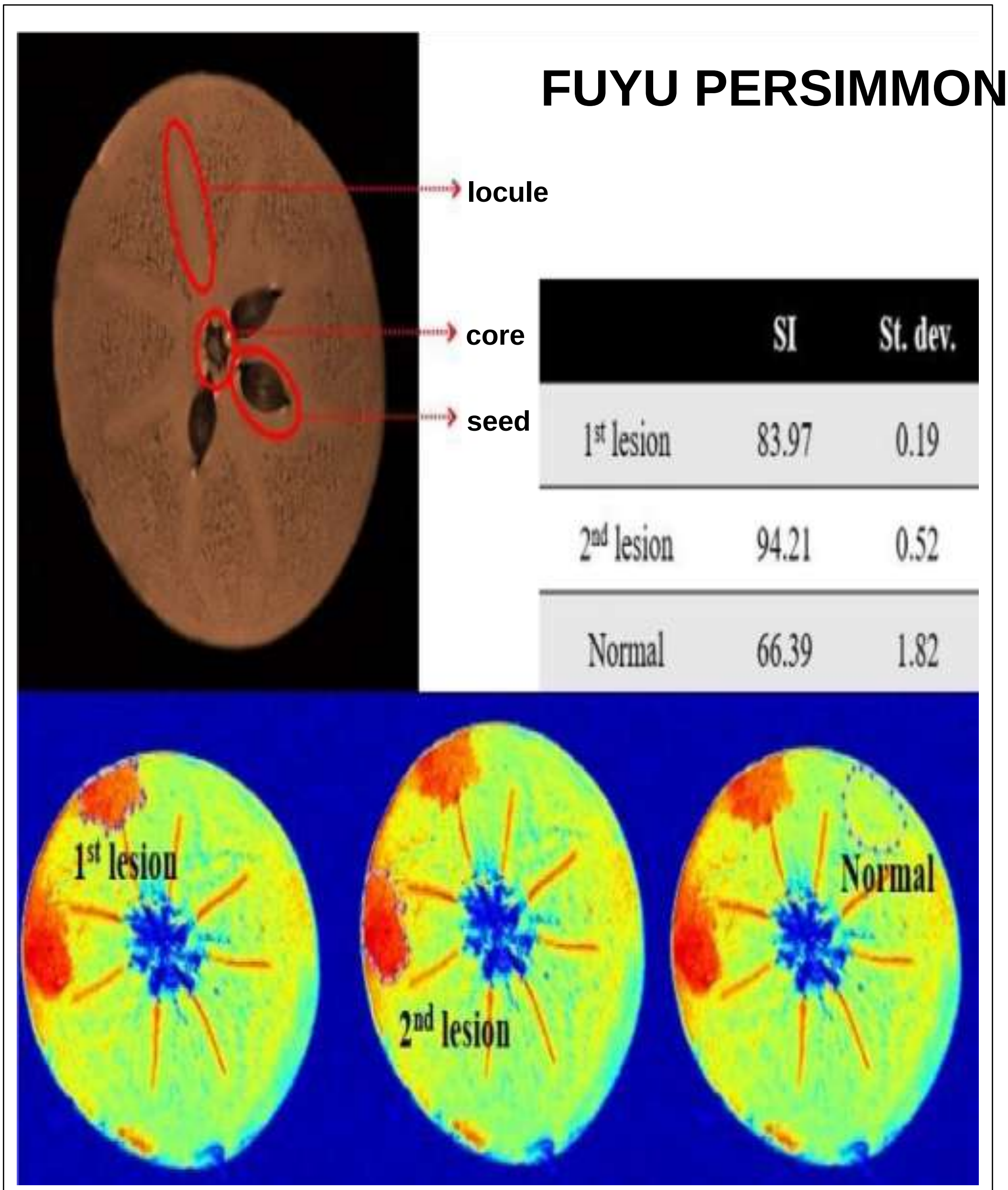
Low Field Nuclear Magnetic Resonance (LF-NMR) is a rapid non-destructive technology widely used in various industries like the food, pharmaceutical and petroleum industries. It entails the measurement of relaxation constants as a magnitude of interactions among nuclear spins and their surroundings. MRI on the other hand involves atomic particles interaction with an external magnetic field to emit energy at a particular frequency (Bushong & Clarke, 2015). The emitted signals represent the imaged tissue structures (Bushong & Clarke, 2015). Magnetic resonance imaging (MRI) further allows visual observation of the inner parts of foods based on the principle of NMR. MRI gives not only information about the chemical composition and internal structure of certain foods, but also permits observation of internal compositional and structural modification of foods after different agricultural practices and industrial possessing. The final physical and mechanical properties of food could be influenced by information acquired from this data which leads to determination of desired structures. MRI technique may provide information through T1, T2, chemical shifts and proton density measurements with 2D and 3D spatial distributions. LF-NMR and MRI serve as suitable cost-effective techniques for assessing the properties of water distribution and states in food, indirectly reflecting food quality. Study done by Song et al. (Song et al., 2018) proved that LF-NMR and MRI could monitor water mobility changes in “Abalone” when applied to reduce drying time and uneven moisture distribution in drying. The transverse relaxation time of immobilized water was seen to fall with a rise in numbers of freeze–thaw cycles in chicken breast based on LF-NMR (Ali et al., 2015). Shi et al. (Shi et al., 2018) stated successful subjection of a mushroom species (Tricholoma matsutake) to LF-NMR and MRI analyses during drying. Pereira and Colnago (Pereira & Colnago, 2012) who determined the moisture content and obtained correlation coefficients between moisture content and T2 intensity values of NMR of > 0.96 also assessed the use of LF-NMR in beef. (Kreyenschulte et al., 2015; Ramanjooloo et al., 2009) successfully applied LF-NMR in direct monitoring of fermentation process.

Even though online LF-NMR and MRI are relatively new techniques in food science, many studies have utilized these techniques in diverse fields in food science. However, the outcomes of these studies utilizing LF-NMR and MRI in diverse food-based applications have not been reviewed critically. This review systematically evaluated the application of LF-NMR and MRI in food quality, food processing, 3D printability, food authentication and sensory evaluation. Limitations and future prospects of LF-NMR and MRI applications were highlighted and discussed briefly in this review.

2. APPLICATION OF LF-NMR AND MRI IN FOOD

2.1 Quality control

LF-NMR and MRI have been of great importance when it comes to its utilization in the analysis of food quality. There are quite a number of studies where these techniques have provided insights on food quality. A variety of studied that assessed microbiological, physical and chemical properties in different foods utilized LF-NMR/MRI to monitor food quality (Gostan et al., 2004; Gudjónsdóttir et al., 2011; Pykett, 2000; Zehl et al., 2011). Pykett (Pykett, 2000) and Gudjónsdóttir et al., (Gudjónsdóttir et al., 2011) applied MRI to examine the microbial quality of fruits and vegetables as well as meats respectively. The conventional approach to examining the microbiological quality in food involves testing representative samples at the various stages of production and the final products. This approach does not provide full assurance of food safety and quality as only representative samples are examined. MRI gives real-time detection of microbial changes in the foods. LF-NMR was able to monitor fish spoilage based on correlation between NMR parameters with total viable counts (TVC) of H2S-producing bacteria (Gudjónsdóttir et al., 2011). Cucumbers with fungus (Mycosphaerella sp.) infection could be differentiated quickly from healthy ones by MRI (Hall et al., 1998). LF-NMR/MRI has been applied to study chemical attributes related to product quality. Ma et al., (Ma et al., 2021) carried out a research to analyze how the combination of radio frequency with ZnO nanoparticles (RFZn) affects the quality of Kungpao Chicken (KPC) using LF-NMR and MRI. They reported that the LF-NMR analysis showed a decline in T22 and T23 and shifted to the lower relaxation direction, which suggested a reduction in water mobility with heat intensity. The MRI images showed a migration of water in the sample from the inner to the outer part. Ultimately, the study proved a minimum effect of RFZn on the food quality. Zehl et al., (Zehl et al., 2011) revealed that LF-NMR could be used to monitor the unique bioactive compounds in medicinal herbal products hence a great tool for quality control. Both consumers and producers consider physical properties like texture as one of the most vital quality indicators in foods (Bourne, 2002). Many researchers have indicated a relationship between MRI image changes and changes in the texture of some fruits and vegetables under diverse conditions (harvest, postharvest and storage). MRI image makes it easy to observe clearly any abnormal changes that occur in the food. Textural changes of fruits like melons, pineapples and peaches during ripening and bruising where clearly shown by MRI (Hall et al., 1998). Butz et al., (Butz et al., 2005) also reviewed LF-NMR/MRI application in the determination of water-related properties and water states of fruits such as kiwi, apples, peaches and oranges. The review compiled sufficient information on the utilization of LF-NMR/MRI to evaluate quality parameters (ripeness, decay and defects) of some fruits and distinguishing between unaffected tissue and holes during diverse conditions (postharvest, storage and transportation). MRI revealed higher signal intensity (SI) for bruised regions of pear due to high free water content in a study that examined the volume of bruises on pear fruit after static loading (Razavi et al., 2018) as shown in Figure 1. MRI provided clear-cut volume measurements owing to its delivery of contrast within the tissues. Online LF-NMR and MRI have been utilized in food quality analysis in quite a number of researches as shown in Table 1. One benefit of LF-NMR and MRI technique is that it can analyze quality changes in food without initiating change in its original state.



	SI	St. dev.
1st lesion	83.97	0.19
2nd lesion	94.21	0.52
Normal	66.39	1.82

Figure 1: High-resolution internal structure MR image of a fuyu persimmon sample and lesions detected by signal intensity (SI) analysis (Ozel & Oztop, 2021)

2.2 Processing

Some researches for online process monitoring and process optimization have utilized conventional analytical methods. Over the years, this method has proven to be time consuming and sample destructive making it challenging to use. The application of LF-NMR/MRI for online process monitoring in food is one of such promising alternative. Recent studies on the application of LF-NMR/MRI in food processing involves the effects of salting on water migration, texture and microstructure of rice (Sangpring et al., 2015) dried sea cucumber rehydration analysis (Geng et al., 2015). MRI have been used a number of times to monitor changes stimulated by fat diffusion and moisture during food processing due to its ability to visualize moisture and fat distribution. Cooking, drying, free drying and extrusion are some of the processes that can be monitored non-invasively by online MRI (Divya et al., n.d.). LF-NMR and MRI have been applied in the area food processing for protein, fat and water analysis as well as monitor the structural, chemical and physical properties in food materials (Gudjónsdóttir et al., 2013; Miklos et al., 2015; Sekiyama et al., 2012; J. H. Shao et al., 2016; X. Shao & Li, 2013; Xin et al., 2013). The feasibility of using LF-NMR (at a frequency of 20 MHz) for online process control in cold-water shrimp processing was demonstrated by Gudjónsdóttir et al. (Gudjónsdóttir et al., 2011). They examined the impact of length of freezing and pre-brining and polyphosphate concentrations on the physiochemical properties of shrimp muscles after cooking the shrimp at 80 °C for 15 s. LF-NMR rapidly detected the changes in the physiochemical property of the shrimp muscle. Changes in phosphate levels, moisture contents, water holding capacity and protein content were observed. Cheng et al., (X. F. Cheng et al., 2014) applied LF-NMR and MRI to analyze the water status in osmotically dehydrated strawberry. Their report showed an increase in the intracellular space of the cytoplasm while the space in the vacuole decreased according to T2 and MRI analysis. Reports by Song et al., (Song et al., 2018) stated categorically that the rehydration time resulted in the reduction in the chewiness and hardness values in abalone during rehydration. They confirmed that the texture profile analysis (TPA) used in this study was time-consuming. The results from LF-NMR and MRI showed a reduction of the rehydration time of Abalone from 144 h to 120 h, which consequently affected the final product quality. Shi et al., (Shi et al., 2018) successfully utilized LF-NMR and MRI to examine the moisture dynamic of Tricholoma matsutake (wild mushroom) in hot-air drying. Results of this study revealed a non- uniformity of moisture during drying with moisture diffusion largely from the center to the surface. One key way to shorten the drying time. When the rate of transformation of immobilized moisture to free moisture is increased, the drying time reduces. The estimation of water content in sausage fermentation was conducted using LF-NMR (Q. Q. Zhang et al., 2017). T1-weighted phantom MR images visually demonstrated an uneven distribution of water in sausages due to vaporization. The mobility of the three different water states (immobilized water T22, bound water T21, and free water T23) could not be clarified by T2 relaxation time. T23 and T22 shifted to short relaxation times during the fermentation process with the sausage water content exhibiting the strongest linear correlation (R2 > 0.92) with T2 spectra. Four proton populations relating to the states of water molecules were revealed by LF-NMR T2 relaxation measurement during the fermentation of natto (Wu et al., 2016). MRI alternatively displayed a full hydration process inside natto indicating a gradual penetration of water molecules from the granules edge to the center. The fermentation processes of *Hansenula polymorpha* and *Ustilago maydis* was observed in real time using Low-field ^{1}H NMR as shown in Fig 2a. This research focused on establishing a cost effective technique for online monitoring of aerobic fermentation process. A flow rate of 80 mL h^{-1} was used leading to a final residence time of 23 min. Reports by Kreyenschulte et al., (Kreyenschulte et al., 2015) stated that glycerol consumption in *H. polymorpha* was precisely assessed regardless of the high amount of complex constituents existing in the medium. Several by-products of itaconic acid and glucose were formed during the cultivation of *U. maydis* with accurate quantification of the relative amount of glycolipids. Results from the fermentation process of *U. maydis* were further compared with that of the offline method. Glucose, glycolipid concentrations and itaconic acid evaluated by online low-field NMR showed a good correlation with the predicted results. Nonetheless, the concentration of glucose estimated by HPLC diverged from the expected results. Kreyenschulte et al., (Kreyenschulte et al.,

2015) reported that this may be due to the uneven mixing of the medium left in the sampling tube hence, leading to the final result showing a lower count of glucose. This results highlights the advantage of online method as sampling and sampling processes are not required.

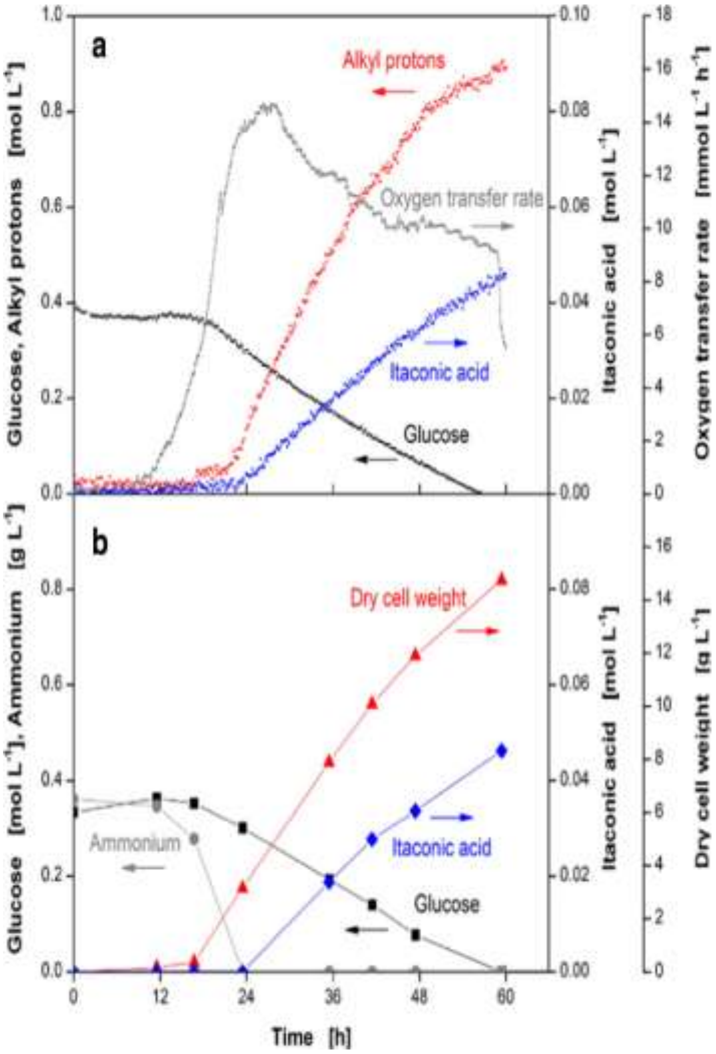


Figure 2: Characterization of Ustilago maydis fermentation via (A) non-invasive online methods using LF-NMR and (B) data obtained from offline sample analytics (Kreyenschulte et al., 2015).

In fig. 3, Wang et al. (T. Wang et al., 2016) used LF-NMR to monitor lipids during the algal lipid fermentation processes. A flow rate of 20 mL min^{-1} with final residence time of < 1 min was used. LF-NMR signals of the extracted algal lipids and the glyceryltrioleate showed a good linear correlation with the lipid quantities. All R2 were more than 0.999 and proved to be rapid and accurate. To further prove the accuracy of this technique, the results were compared to those obtained by GC-MS. Though both methods seem to be comparable, direct analysis with online LF-NMR exhibited reduced sample preparation time and quick analysis time proven the effective application of online LF-NMR in the field of food processing.

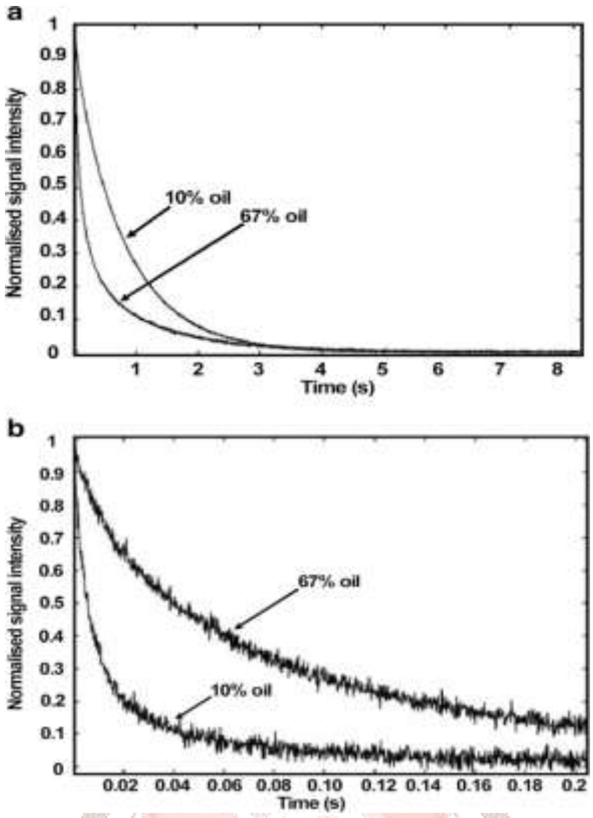


Figure 3: Monitoring of lipids during algal lipid fermentation of Chlorella protothecoides (T. Wang et al., 2016).

2.3 Food authentication

Food authentication is one of the major areas were NMR/MRI technique has been applied. The validation of the authenticity of food products is of great importance owing to its significant economic and health consequences, hence attracts both producers and consumers interest. It is therefore of great importance to introduce a precise and sensitive detection method in food traceability to verify and prevent food frauds. NMR/MRI techniques have been applied extensively to detect authentication within different foods (Bertelli et al., 2010; Ellis et al., 2012). The most common factors inspected are geographical origin (Alonso-Salces et al., 2010) variety (Clausen et al., 2014) harvest period (Agiomyrgianaki et al., 2012) type of production (Laghi et al., 2014) adulteration with lower price and quality products (Akanbi & Barrow, 2018; Araujo et al., 2018). Many studies have utilized high field NMR spectroscopy for adulteration detection (Marcone et al., 2013). However, there is an increasing trend in recent years in the use of LF-NMR technique in the control of authenticity of foods. Wang et al., (J. Wang et al., 2018) used the LF NMR/MRI method to distinguish adulterated shrimps with gel injection. The spin-spin relaxation rates reduced when the shrimps were injected with Carrageenan. Discriminant analysis (DA) based on LF-NMR relaxometry measurements was applied to assess the adulteration ratios of peanut oil adulterated with palm oil, rapeseed oil and soybean oil (Zhu et al., 2017)(Zhu et al., 2017). According to Hou et al., (Hou et al., 2020), the combination of LF-NMR transverse relaxation data with convolutional neural network (CNN) algorithm could accurately distinguish the pure extra virgin olive oil from the hazelnut and sunflower oil adulterated forms with precision and accuracy of 81.3% and 89.3% respectively. LF-NMR was applied to distinguish between different types of meats and detect adulteration of sunflower oil with lard (Jakes et al., 2015). Riegel et al., (Riegel SD, 2015) applied NMR to investigate the adulteration of olive oil with soybean oil. In this study, solutions in CDCl3 of olive oils mixed with 5–60% of soybean oil were measured at

60 MHz. Plotting the percentages of bis-allylic protons against that of soybean oil produced a straight line due to the higher content of PUFAs in soybean oil. With this curve, the extent of adulteration could be easily determined. An LF-NMR method was developed to check the adulteration of *Perilla frutescens* edible oil with 30 times cheaper soybean oil (Kim et al., 2018)(Kim & Seo, 2018). Samples were dissolved in 500 µL of CDCl3 which contained 0.03% TMS (tetramethylsilane) and measured at 43 MHz with a range of 1-6. The most important range for detecting the adulteration of unsaturated Perilla vegetable oil were 2, 3, 4 and 6. The range 2 peak became bigger upon adulteration because it contained fewer methylene units (-CH2-) in PUFAs. Contrastingly, range 4 and 6 peaks were smaller upon adulteration due to their correlation with PUFAs and double bonds respectively. Adulteration with ≥ 6% (v/v) soybean oil was detected. In a study conducted by Krause et al., (Krause et al., 2018), NMR spectra of 75 genuine PEOs, 17 adulterants, 10 other essential oils as well as 10 commercial PEOs were recorded. The NMR fingerprint of genuine PEO was constant hence, making it easy to detect adulterants when skewed at 20%. Non-volatile PEOs (paraffin and ricinus oil) could not be observed by qualitative GC-MS as seen in Fig. 4A. 15 out of 17 adulterants including gurjun balsam were detected with Chemometric data treatment (Mahalanobis distance) based on 0.1-8.1 ppm integration in an increment of 0.01 ppm (Figure 4B). The Mahalanobis distance and 10, 20 or 30% of adulteration with gurjun balsam exhibited a linear correlation. The software detected all adulterated commercial PEOs as well as other essential oils. It was concluded that LF-NMR is complementary to GC-MS and has proven to be a refractive index measurement for the authentication of essential oils. LF-NMR has proven to be an effective tool for food authentication owing to its capacity to analyze large number of compounds in a single snapshot. The utilization of LF-NMR in this area expected to increase in the food industry.

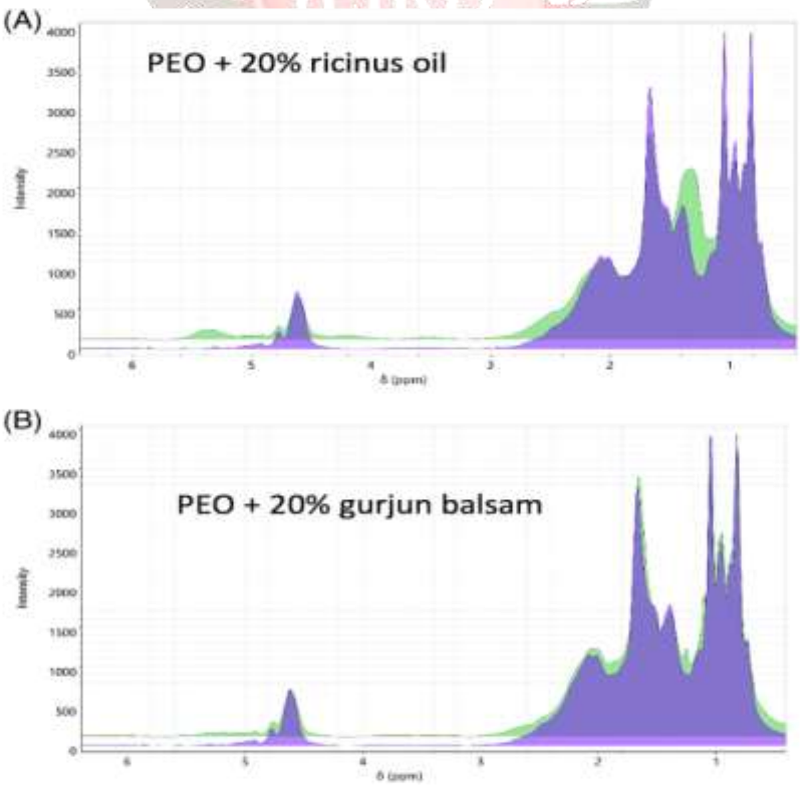


Figure 4: Overlaid 60 MHz ^{1}H-NMR spectra of patchouli essential oil (PEO) pure (in purple) and PEO spiked at 20% with ricinus oil (in green) (A) and gurjun balsam (in green) (Krause et al., 2018).

2.4 3D Printability

Food printing in three dimensions (3D) is a quick food prototype technique based on 3D printing technology. This new technique can generate intricate edible shapes as well as alter the texture of the food and nutrients needed for a certain diet (Uribe-Alvarez et al., 2021). To construct the desired 3D design, extrusion-based 3D printing, which is one of the most prevalent 3D food printing processes, depends on the layer-by-layer coating of a continuous and densely concentrated flowing ink (Godoi et al., 2016). Extrusion-based 3D printing technology has been used to print food materials including cheese (Le Tohic et al., 2018), mashed potatoes (Feng et al., 2020), chocolate (Mantihal et al., 2019), meat paste (L. Wang et al., 2018) and dough (Yue et al., 2021). Rheological properties including pseudoplasticity, rapid recovery performance and viscoelasticity are key to evaluating the 3D printability of food ink (Pérez et al., 2007). LF-NMR has been used to investigate the rheological properties of food ink and the correlation of proton signals. Reports showed that parameters such as the corresponding peak areas and relaxation time were strongly correlated to the viscoelastic properties and shear thinning of food inks (Chen et al., 2021; Phuhongsung et al., 2020). Du, Zhang, and Chen (Du et al., 2021) used LF-MNR to investigate how different levels of whey protein powder (0, 5, 10, 15, 20, 25 and 30%, w/w) combined with konjac gel paste could have an effect on 3D printing performance and supportability. In this study, whey powder improved the rheological properties and significantly elevated storage modulus (G′), loss modulus (G″) and apparent viscosity of the gel. The inclusion of whey protein transformed the microstructure to a new thicker structure and improved the textural properties of the gel which in turn enhanced flowability during extrusion and aided in printing. Based on the LF-NMR results they concluded that the printing performance with 20% whey protein was ideal for 3D printing of konjac-whey protein gel system. Gudjonsdóttir et al., (Gudjónsdóttir et al., 2019) applied principal component analysis of LF-NMR relaxation data to assess the effect of salt content and various processing methods of surimi preparation on the quality of 3D printed surimi. Chen, Hui-zhi; Zhang, Min; Yang and Chao-hui (Chen et al., 2021) conducted a study to examine the potential of low field nuclear magnetic resonance (LF-NMR) and dielectric characteristics (at 915 and 2450 MHz) to predict the rheological properties and estimate the printability of surimi gels at different concentrations of NaCl and water. A correlation map between rheological, LF-NMR and dielectric parameters (at 915 MHz and 2450 MHz) was constructed as shown in Fig. 5. A2b was positively correlated ($r > 0.7$) with K, G′, G″, G*, G′ -10, G″-10, G*-10. A2b, A21 and A, A23 showed a higher correlation with K, G′, G″, G*, G′ -10, G″-10, G*-10, especially the G′ and G* ($r > 0.9$) when compared. The results showed good correlations between LF-NMR T2 relaxation time and peak area (A22) with the rheological properties.

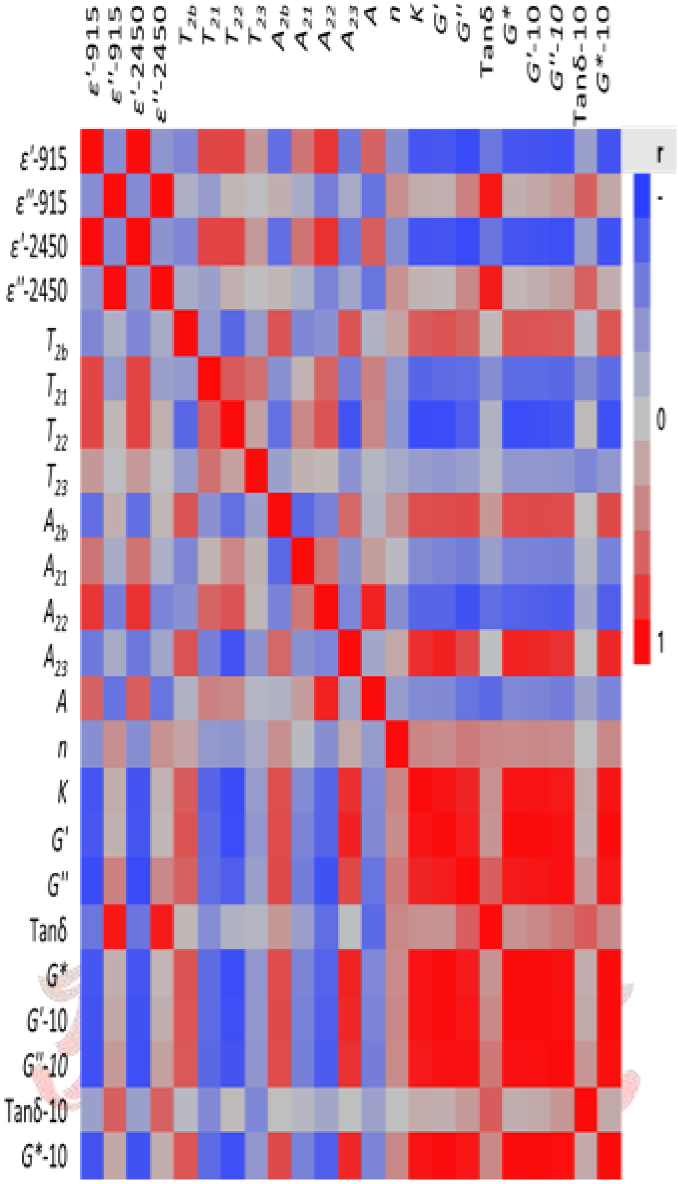


Figure 5: Correlation map between rheological, LF-NMR and dielectric parameters. ϵ’-915, ϵ’’-915 were the values at 915 MHz; ϵ’-2450, ϵ’’-2450 were the values at 2450 MHz; G′ , G″, G* were the values at 1 rad/s; G′ -10, G″-10, G*-10 were the values at 10 rad/s (Chen et al., 2021).

Table 1 summarizes the results of classifying the printability of surimi gels using canonical discriminant function based on the LF-NMR or dielectric parameters. The results observed based on dielectric parameters showed that 85 samples were correctly assigned to their corresponding categories. Interestingly, the results obtained based on LF-NMR T2 parameters gave an impeccable classification of the samples with a 100% of correctly classified samples. They concluded that, comparing the two monitoring techniques, canonical discriminant analysis based on LF-NMR T2 parameters presented a better classification of printability of surimi gels. Also, predicting dynamic viscoelastic properties of surimi gels using PLSR models based on LFNMR T2 parameters demonstrated robustness and a better predictive accuracy.

Table 1: Classification of printability of surimi gels using canonical discriminant function based on the LF-NMR or dielectric parameters (Chen et al., 2021).

		II					
Dielectric parameters	Samples A0-3	20	4			24	83.3
	Samples B0-3	4	19	1		24	79.2
	Samples C0-3	2		22		24	91.7
	Samples D0-3				24	24	100.0
	Total					96	88.5
LF-NMR T_2 parameters	Samples A0-3	24				24	100.0
	Samples B0-3		24			24	100.0
	Samples C0-3			24		24	100.0
	Samples D0-3				24	24	100.0
	Total					96	100.0

2.5 Food packaging

Packaging is a broad technology, which includes four functions: protection, convenience of use, communication and containment of packaged products in appropriate environmental conditions. The selection and design of appropriate packaging materials are crucial when it comes to the protection of food products. Food packaging with the proper selection and optimization provides better maintenance, storage and handling of foods. Glass, steel, paper, aluminum and polymeric materials are examples of packaging materials used in the food industry. Many packaging technologies have been developed to enhance fresh food shelf life and meet market demand (Kim & Seo, 2018). Several studies have reported that appropriate oxygen and carbon dioxide concentration in packaging microenvironment can regulate enzyme browning, maintain K+/Na+ homeostasis as well as control water loss in fruits (Li et al., 2018). LF-NMR/MRI in recent times has proven capable of investigating the properties of packaging materials and optimizing food-packaging materials. Pentimalli et al., (Pentimalli et al., 2000) applied NMR to determine the effects of gamma irradiation on food packaging polymers (poly-butadiene, styrene–acrylonitrile, polystyrene, acrylonitrile and high impact polystyrene). Results of their study showed that polystyrene is best for packaging food that may undergo irradiation. The degradation of Robiola cheese without package and in a composite paper foil package was assessed over a 7-day period at room temperature (15 °C). Compared with the cheeses stored in the package, the spectrum of the cheese without package exhibited more variation in the concentration of certain chemical compounds (Lamanna et al., 2008). In a research conducted by J. Jiang, et al., (Jiang et al., 2020) to develop a biodegradable active film for the preservation of peaches, LF-NMR and MRI were used to monitor the water status and migration in peaches packaged in different active film packages. LF-NMR/MRI could trace the movement of water, aging and corruption of the peaches in the various active packaged films. Results obtained from this study served as an effective reference for active fresh-keeping packaging development and utilization in vegetables and fruits.

3. LIMITATIONS AND FUTURE PROSPECTS

Low-field nuclear magnetic resonance (LF-NMR) and magnetic resonance imaging (MRI) have become fast emerging technologies utilized in food science. Nonetheless, some shortcomings prevent the widespread use of these techniques, which is a wakeup call for the need of further improvement. Some limitations associated with the instruments include magnetic field inhomogeneity, small size of the measurement bore and relatively slow measurement speed. The need for temperature control during measurements in food processing units is another limitation that comes with their application in food processing. In situations where a single system is applied, low sensitivity has been identified as a common drawback related to the application of LF-NMR and MRI. In order to overcome this limitation, many researchers have recommended the integration of two or more systems to aid in high precision, stability and sensitivity in prediction. From the study of Lv et al. (Lv et al., 2018), LF-NMR/MRI could not predict accurately the moisture content of all the six different varieties of vegetables directly. The establishment of an all- inclusive technology for NMR technique for particular food products is recommended with considerations made to the diversity of food varieties. Also, LF-NMR/MRI are less applied at industrial/farm level due to the cost involved and the technical limitations of super-conducted magnets. Permanent magnets operating in higher frequencies may be developed to increase the application of this technique at industrial level. In addition, Improvements in spectral databases for food components will be vital for future application of LF-NMR/MRI in food. Collaborations between NMR scientists, academicians and the food-agricultural industry is needed to achieve this. Lastly, online-based analyses with LF-NMR/MRI require technical skills. This has led to the unpopularity of the technology in a wider context. Advances in the technology to make it more user friendly may be vital to drive its application in extensively.

CONCLUSION

The introduction of LF-NMR and MRI technology have proven to be effective in food science based on the above gathered literature. LF-NMR and MRI is able to monitor and asses real time changes during food processing, providing a quick process analysis without the need for sample preparation and further calibration. LF-NMR and MRI proved to be a non- invasive and efficient tool to ensure the quality and authenticity of food during storage and processing levels. Whiles LF-NMR provides quantitative data on the physical and chemical composition of food, MRI provides a visual information on the internal tissues of food. Food and agricultural commodities have lower profit margins than pharmaceuticals, which may lead to the preference for lower-cost analytical techniques in these industries. A further advancement in a more effective and less costly NMR/MRI technique is expected to play a bigger role in industrial applications and could become an important aspect of food analysis in the food industry in the coming decades.

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