

RESEARCH ARTICLE OPEN ACCESS

Hydration and Structural Changes of Almonds During Water Treatment at Different Temperatures Investigated by MRI and NMR

Lena Trapp¹ | Tanja Eirich¹ | Hilke Schacht² | Hermann Nirschl¹ | Gisela Guthausen^{1,3}

¹Institute of Mechanical Process Engineering and Mechanics, Karlsruhe Institute of Technology, Karlsruhe, Germany | ²Fraunhofer Institute for Process Engineering and Packaging IVV, Freising, Germany | ³Engler-Bunte-Institut, Water Chemistry and Technology, Karlsruhe Institute of Technology, Karlsruhe, Germany

Correspondence: Gisela Guthausen (gisela.guthausen@kit.edu)

Received: 28 February 2026 | **Revised:** 15 September 2026 | **Accepted:** 18 September 2026

Keywords: almonds | blanching | hydration | magnetic resonance imaging (MRI) | nuclear magnetic resonance (NMR) | swelling | water treatment

ABSTRACT

Hydration and water uptake during blanching critically influence texture and stability of almonds, yet the multiscale structural changes remain poorly characterized. This study employs in situ magnetic resonance imaging (MRI) and ex situ nuclear magnetic resonance (NMR) techniques to provide a comprehensive analysis from millimeter to micrometer scales. The objective was to quantify how water penetrates and reorganizes almond tissue and how these changes affect the microstructural organization of lipids and intrinsic molecular mobility. In situ MRI at 200 MHz was used to monitor water front propagation, swelling, cavity formation, and local relaxation changes in almonds at 20–80°C. Radial signal profiles were analyzed with Boltzmann fits to extract characteristic kinetic parameters, revealing temperature-dependent hydration dynamics and hierarchical swelling behavior. Ex situ NMR, including pulsed field gradient stimulated echo (PFG-STE) diffusion and Carr–Purcell–Meiboom–Gill (CPMG) transverse relaxation experiments at 400 MHz, probed lipid mobility and microstructural organization in untreated, industrially blanched, and self-blanched almonds (4 min and 3 h at 80°C). Results indicate that short-term blanching preserves diffusion behavior consistent with geometrically restricted lipids in intact oleosomes. In contrast, prolonged blanching (3 h) produces diffusion-time-dependent apparent diameters and rapidly relaxing components, suggesting increased water–matrix interactions and structural heterogeneity. Overall, the combined MRI and NMR approach enables linking macroscopic hydration dynamics to microscopic molecular mobility, providing a multiscale understanding of almond swelling and lipid redistribution. These methods offer a robust framework for studying hierarchical structural changes in plant-based foods under thermal treatment.

Practical Applications: The insights into almond hydration, swelling, and lipid mobility obtained via in situ MRI and ex situ NMR are directly relevant for industrial processes, such as blanching and pasteurization. Understanding how water penetrates and interacts with the almond matrix enables optimization of processing parameters to maintain texture, prevent defects, and preserve lipid integrity. These measurements also provide a nondestructive way to monitor batch-to-batch variability and can inform the design of novel nut-based products, improve shelf-life stability, and be extended to other nuts and seeds where water–matrix interactions influence processing outcomes.

Abbreviations: ABS, acrylonitrile butadiene styrene; CPMG, Carr–Purcell–Meiboom–Gill; MCPR, Murday–Cotts–Packer–Rees; MRI, magnetic resonance imaging; MSME, multi-slice multi-echo; NMR, nuclear magnetic resonance; PFG-STE, pulsed field gradient stimulated echo; RARE, rapid acquisition with relaxation enhancement; rf, radiofrequency; ROI, region of interest.

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *European Journal of Lipid Science and Technology* published by Wiley-VCH GmbH.

1 | Introduction

Almonds are widely consumed due to their high nutritional value, desirable sensory properties, and content of lipids, proteins, and bioactive compounds. Beyond direct consumption, almonds are commonly used in processed forms, such as in baked goods, marzipan, chocolate, or as plant-based milk alternatives. A key processing step for almonds is blanching, in which almonds are briefly treated with hot water [1–3]. This process primarily facilitates the removal of the thin seed coat (testa) and reduces microbial load, thereby improving both visual quality and food safety. In addition, blanching can influence the molecular structure of almonds, particularly the intracellular oil droplets (oleosomes), affecting the physicochemical properties of the final product.

Oleosomes are spherical lipid droplets, 2–3 μm in diameter, stabilized by a phospholipid–protein membrane [4–6]. They store the majority of almond oil intracellularly, protecting it from enzymatic degradation and oxidation [7, 8]. Structural changes induced by thermal or mechanical processes can compromise oleosome integrity, leading to increased oil mobility, release of lipids, and reduced oxidative stability [9]. These effects are practically relevant, as they can contribute to phenomena, such as fat bloom in chocolate or texture changes in almond-based beverages [10–13].

Despite the widespread use of blanching, the structural and molecular changes occurring in almonds during the process remain poorly understood. In particular, systematic investigations of hydration, oil distribution, and microstructure at different temperatures and over extended soaking times—conditions relevant not only to blanching but also to applications, such as plant-based milk production—are lacking. A deeper understanding of these processes can help optimize almond quality in various food products.

Nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) provide complementary insights into these processes. MRI enables noninvasive, in situ visualization of structural changes in almonds on the mesoscopic scale ($\sim 50\ \mu\text{m}$ to mm). To better interpret these observations, additional NMR diffusion and relaxation measurements were made. Diffusion measurements investigate the mobility of oil storage compartments at the microscopic scale, whereas relaxation measurements provide information on intrinsic molecular mobility and interactions between almond components and water. Together, these approaches allow a multiscale understanding of hydration, structural changes, and lipid dynamics.

In this study, a dedicated flow-through glass apparatus was developed to allow in situ investigations of almonds under controlled temperature and water conditions. This setup enables systematic analysis of hydration and structural changes at temperatures of 20°C, 40°C, 60°C, and 80°C over prolonged soaking periods, covering both classical blanching conditions and other applications, such as plant-based milk production. The aim is to elucidate the relationships between processing parameters (temperature and soaking duration) and resulting changes in almond microstructure and oil mobility, providing

fundamental insights into water–lipid interactions that are critical for optimizing processing methods and maintaining product quality.

2 | Materials and Methods

2.1 | Almonds

Raw almonds of Californian origin were purchased from a local supermarket (Germany). The almonds were marketed as natural, unprocessed kernels with intact seed coat (testa). No further analytical characterization (e.g., moisture content, lipid content, or cultivar differentiation) was performed prior to the experiments.

For the in situ blanching experiments, whole almonds of typical commercial size were selected. The only selection criterion was geometric compatibility with the flow-through glass apparatus; kernels exceeding the inner diameter of the sample chamber were excluded to ensure proper positioning and homogeneous water exposure during MRI measurements.

For comparative ex situ NMR measurements, commercially blanched almonds of Californian origin (seed coat removed by industrial hot-water treatment) were obtained from the same retail source. These samples were used exclusively for diffusion and relaxation measurements and were not subjected to additional in situ blanching within the glass apparatus. The comparison aimed to distinguish structural and molecular differences between laboratory-blanched almonds and conventionally processed almonds.

2.2 | Experimental Setup for In Situ MRI Measurements

2.2.1 | MRI-Compatible Blanching Apparatus

To investigate hydration- and temperature-induced structural changes of almonds under controlled water immersion, an experimental setup was developed that enables in situ MRI measurements, whereas the sample is continuously exposed to temperature-controlled water (Figure 1). The investigated temperature range (20–80°C) covers both ambient hydration conditions and temperatures relevant to industrial blanching processes, which are typically performed by immersion in hot water at elevated temperatures for short time periods [1–3]. A key requirement was to ensure that the almond remained at an identical spatial position throughout the entire experiment while allowing homogeneous water flow around the kernel. Furthermore, full compatibility with the MRI environment was essential, prohibiting the use of metallic components and limiting the overall dimensions of the setup to the inner diameter of the MRI probe.

The central element of the apparatus is a custom-made double-walled glass tube with vacuum insulation (Figure 1, left), similar to a roasting device from a previous study [14]. The outer dimensions were constrained by the inner diameter of the MRI probe.

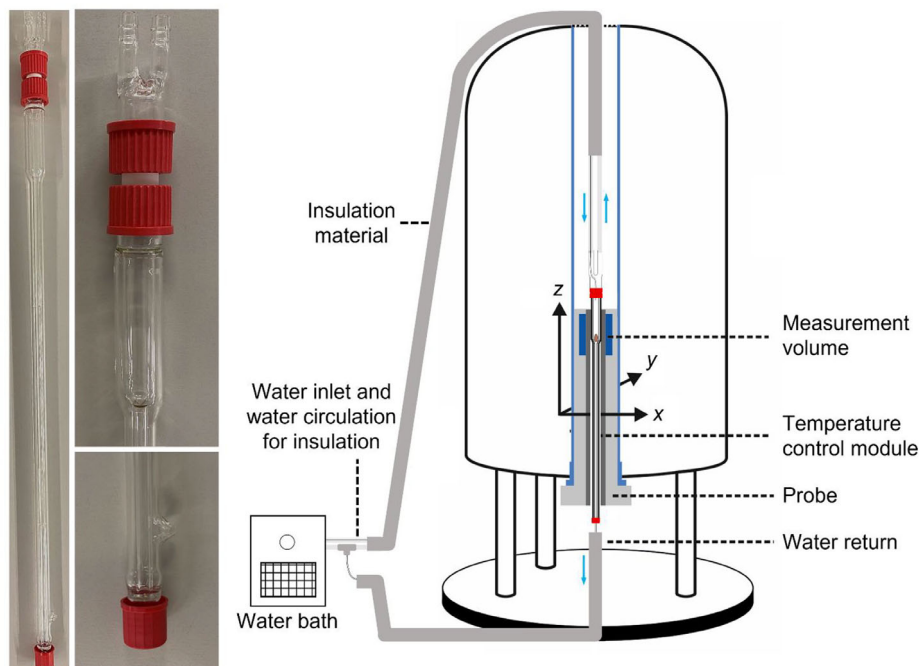


FIGURE 1 | Experimental setup for in situ blanching in the MRI. Left: Double-walled glass tube designed for use in the MRI probe. The tube features a constricted section that reduces the effective water volume, thereby shortening the heating time, and simultaneously provides a defined placement position for an almond. This position ensures that the almond is located within the sensitive region of the magnet and probe while remaining sufficiently surrounded by hot water. Right: Schematic representation of the setup. Temperature-controlled water is circulated from top to bottom through the glass tube using a water bath and pump via insulated hoses. The glass components are connected by screw fittings with integrated septa to ensure a leak-tight assembly and to prevent water from entering the probe. Water inlet and outlet are realized using thin tubes guided through the septa and combined via a T-junction before returning to the water bath.

The vacuum layer between the glass walls provides efficient thermal insulation, preventing excessive heat transfer to the probe and gradient system.

The inner glass tube features a constricted section that reduces the effective water volume within the measurement region, thereby shortening heating times and improving temperature stability. Simultaneously, this constriction serves as a defined support for a single almond. In the final configuration, this position coincides with the sensitive region of the radiofrequency (rf) coil and magnet, ensuring optimal signal detection. Due to the natural geometric irregularity of almonds, complete sealing of the cross-section is avoided, and continuous water flow around the kernel is maintained at all times.

To prevent movement or flotation of the almond during water circulation, the sample was gently fixed from above using a 3D-printed holding stamp made of a photopolymer resin with mechanical properties comparable to acrylonitrile butadiene styrene (ABS). The stamp contains recesses to allow unobstructed water flow and is positioned through a central opening in a septum, which simultaneously ensures sealing of the system. The fixation guarantees mechanical stability within the spatial resolution of MRI while maintaining homogeneous thermal exposure.

The upper glass section is connected to the main tube via two screw fittings equipped with integrated septa to ensure leak-tight assembly and to prevent water intrusion into the probe. Two hose connectors are located at the upper fitting. One connector

serves as the water inlet: A thin inner tube passes through the septum into the measurement chamber, enabling controlled filling and downward flow of temperature-regulated water. The second connector provides the outlet for returning water. At the lower end of the long glass tube, an additional screw fitting with septum allows the insertion of a thin outlet tube. The returning water streams are merged via a T-junction before reentering the temperature-controlled water bath. Because of the strong magnetic field, the water bath and pump were positioned outside of the magnet's stray field.

To minimize temperature losses along the tubing path between the water bath and magnet, all hoses were thermally insulated using foam insulation sleeves. In particular, the thin inlet tube supplying the measurement chamber was guided coaxially within a thicker hose that was simultaneously flushed with hot water (cocurrent configuration), thereby reducing heat dissipation. This design ensured that the temperature set at the water bath was reliably maintained inside the sample chamber.

Prior to MRI experiments, off-magnet tests were made to evaluate temperature stability and thermal insulation performance. Water temperature was measured directly inside the glass tube using a temperature sensor, whereas the outer glass surface temperature was monitored using an infrared thermometer. At a set temperature of 80°C, the water bath reached thermal equilibrium after approximately 11 min. The displayed temperature of the water bath was found to be consistent with direct measurements and was therefore used as the reference value during MRI experiments, where direct temperature monitoring inside the

magnet was not feasible. The temperature difference between water bath and measurement chamber was negligible under steady-state conditions.

To ensure safe operation within the MRI probe, the external surface temperature of the double-walled glass tube was monitored during continuous circulation of 80°C water. Even after 1 h of operation, the outer surface temperature did not exceed 25°C, confirming effective thermal insulation and compatibility with the probe. Although slight heating of the probe during extended measurements cannot be fully excluded, potential effects are expected to manifest primarily as a reduction in the quality factor of the resonance circuit [15].

A schematic representation of the complete setup is shown in Figure 1.

2.2.2 | MRI Measurements of Almonds During Water Immersion

All MRI experiments were performed on a Bruker 200 MHz Avance III HD spectrometer equipped with a super wide bore (SWB) magnet (Bruker BioSpin GmbH, Germany) operating at 4.7 T and Great 60 gradient amplifiers. A 25-mm ^1H -probe and the rapid acquisition with relaxation enhancement (RARE [16]) pulse sequence were used. ^1H -images were acquired, whereas individual almonds were placed in the custom glass apparatus and immersed in water over several hours. In situ measurements were performed at 20°C, 40°C, 60°C, and 80°C.

During preliminary tests, the effect of water circulation on image quality was evaluated. Active water flow induced inflow and outflow artifacts [17]: Spins entering the excitation volume exhibit higher longitudinal magnetization than the stationary sample, resulting in local signal enhancement above the almond, whereas spins leaving the excitation volume produce signal loss below the almond. These flow-induced effects caused image blurring and reduced visibility of almond structures. To avoid these artifacts, water circulation was disabled during all subsequent measurements.

The appearance of almonds in MR images depends strongly on the choice of acquisition parameters, which determine the image weighting (e.g., T_1 or T_2) and thus the contrast between the almond and surrounding water. Depending on the chosen acquisition parameters, the almond and the surrounding water exhibit differing signal intensities. By adjusting these parameters, either the almond or the water has higher signal intensity relative to the other. Different weightings highlight different structures, components, or dynamic processes within the almond. Therefore, no single parameter set is universally optimal; the choice must be guided by the specific structures or processes of interest. Additionally, even if one structure or process is visible under a given parameter set, other processes may occur simultaneously but remain undetected.

For room-temperature measurements, a predominantly T_1 -weighted contrast was applied. Short repetition times (t_R) and echo times (τ_e) were chosen to optimize visualization of almond

structures. At elevated temperatures, further adjustments of the MRI parameters were necessary to account for temperature-dependent effects on signal intensity and relaxation times. T_1 and T_2 relaxation times increase, altering the image contrast. To compensate, t_R was increased for sufficient recovery of longitudinal magnetization, and τ_e was decreased to enhance signal differences between almond and water. Table 1 summarizes the acquisition parameters.

2.2.3 | Image Analysis Using the Ring Method

To quantify structural changes in almonds over time, MR images were analyzed using a modified ring method (Figure 2) [18].

For each image, a binary mask was generated around the almond to define the region of interest (ROI). The mask was then successively scaled inward toward the almond center in one-voxel increments, and the signal intensity was averaged along the contour at each step. This process yields a signal profile $S_{\text{Avg}}(r)$, as a function of the reduced radius r and time t , with t denoting the elapsed time because the almond was immersed in water during the in situ experiment. The reduced radius represents the mean radial position within the mask, decreasing toward the almond center. Statistical uncertainty increases at smaller radii due to averaging over fewer voxels. This method allows time-resolved, spatially resolved quantification of water penetration and structural changes in the almond.

2.3 | Experimental Setup for Ex Situ Integral Diffusion and Relaxation Measurements

To further investigate the mobility of oil and the microscopic structure of almonds—which may change due to water contact—complementary diffusion and relaxation measurements were performed. Compared to the MR images, these experiments allow a more detailed assessment of translational and intrinsic oil mobility as well as smaller structural features. All integral ex situ NMR measurements were performed on an Avance Neo 400 MHz Bruker spectrometer equipped with a wide bore magnet and a 5-mm DiffBB gradient probe. The acquisition parameters for the experiments are summarized in Table 1.

Cylindrical almond pieces with a diameter of 4 mm were obtained from 10 untreated almonds, 10 commercially blanched almonds, and 6 self-blanched almonds (3×4 min, 3×3 h). The self-blanched samples were immersed in water on a hot plate for the respective durations. The pieces were placed in 5-mm NMR tubes with a filling height of ~ 1 cm.

Pulsed field gradient stimulated echo (PFG-STE [19, 20]) experiments were performed on all samples to characterize oil mobility and oleosome size. Two distinct spectral peaks were observed for all almonds, and signal integration was performed separately for each peak. The equivalent volume-weighted mean oleosome diameter $d_{33, \text{eq}}$ and the distribution width σ_{MCPR} were extracted from the diffusion signal decays using the MCPR approach (Murday and Cotts, extended by Packer and Rees) [21–24]. This model assumes spherical oleosomes with geometrically restricted

TABLE 1 | Acquisition parameters for ^1H nuclear magnetic resonance (NMR) experiments on almonds.

Pulse sequence		RARE		PFG-STE	CPMG	MSME
		200 MHz		400 MHz	400 MHz	200 MHz
		RT	HT			
Number of scans N_{AV}	[-]	6	4	8	16	16
Spectral width—SW	[ppm]	—	—	50	50	—
Data points	[-]	—	—	1024	1024	—
Repetition time— t_{R}	[s]	0.8	2	2.5	4	0.8
Echo time— τ_{e}	[ms]	4.67	3.40	—	0.2	4.2
RARE factor—RF	[-]	6	4	—	—	—
Number of increments	[-]	—	—	32	64	64
Diffusion time— Δ	[s]	—	—	[0.2, 0.5]	—	—
Gradient duration— δ	[ms]	—	—	5	—	—
Gradient amplitude— g	[T m $^{-1}$]	—	—	[0.5, 15.92]	—	—
Field of view—FOV	[mm $\times$ mm]	25 $\times$ 25	20 $\times$ 20	—	—	25 $\times$ 25
Size of data matrix	[px $\times$ px]	256 $\times$ 256	256 $\times$ 256	—	—	256 $\times$ 256
Voxel size	[$\mu\text{m} \times \mu\text{m}$]	98 $\times$ 98	78 $\times$ 78	—	—	98 $\times$ 98
Slice thickness	[mm]	0.8	0.8	—	—	0.8
Slice gap	[mm]	0.2	0.2	—	—	—
Temperature— T	[K]	293	353	293	293	293
Measurement time	[min]	2:33	6:32	10	28	42:16

Abbreviations: CPMG, Carr–Purcell–Meiboom–Gill; MSME, multi-slice multi-echo; PFG-STE, pulsed field gradient stimulated echo; RARE, rapid acquisition with relaxation enhancement; RT, room temperature; aHT, elevated temperature ($\geq 40^\circ\text{C}$).

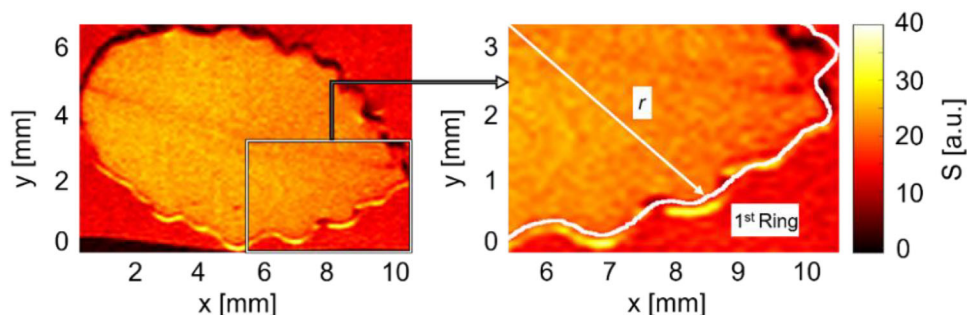


FIGURE 2 | Application of the ring method [18], adapted for the analysis of almonds. The almond is segmented using a binary mask, which defines its contour and the region of interest. Signal intensity is spatially averaged (S_{Avg}) as a function of the reduced radius r . Unlike the original application to filtration experiments with cylindrical membrane channels, ideal concentric rings are not used; instead, the almond contour is successively scaled toward the center while preserving its shape. At each scaling step, corresponding to a radial increment of one pixel, S_{Avg} is determined, resulting in profiles of S_{Avg} as a function of r and time t .

diffusion of the contained oil, and for polydisperse systems, the size distribution follows a log-normal distribution. MATLAB scripts from the Pro²NMR group were used to fit the diffusion data and extract $d_{33, \text{eq}}$ and σ_{MCPR} .

Complementary Carr–Purcell–Meiboom–Gill (CPMG [25, 26]) experiments were performed on a subset of samples (one untreated and one 3 h self-blanching almond) to determine the transverse relaxation time (T_2), thereby providing infor-

mation on intrinsic molecular mobility. The relaxation data were used primarily to explain details of diffusion measurements.

2.4 | Experimental Setup for Ex Situ Spatially Resolved Relaxation Measurements

To gain further insight into the effects of water exposure on almond structure, spatially resolved relaxation measurements

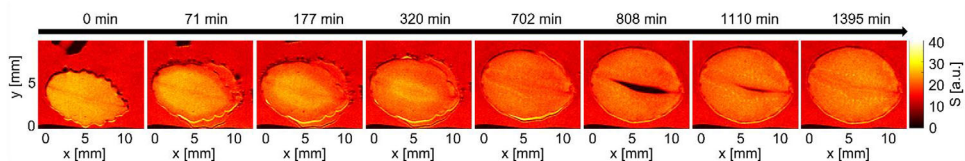


FIGURE 3 | Sagittal ^1H MR images of an almond immersed in water at room temperature over a 24 h period. Shown here are exemplary images from a larger measurement series, acquired immediately after immersion and at selected time points during the experiment. Initially, the almond exhibits higher signal intensity than the surrounding water, resulting in strong contrast. Over time, a radially progressing decrease in signal intensity from the outer regions toward the center is observed, indicating the inward propagation of a water front. During this process, water accumulates beneath the almond skin, causing its detachment from the kernel, which is visible at 71, 177, and 320 min. After the water front has fully penetrated into the almond, a low-signal region near the noise level appears between the two almond halves, corresponding to an air-filled cavity. Subsequent swelling of the almond matrix leads to the closure of this cavity, accompanied by an overall increase of almond volume.

were performed. These measurements complement the integral relaxation experiments, providing additional information on changes in T_2 due to water infiltration.

The experiments were measured on the same Bruker 200 MHz spectrometer that was used for the in situ MRI experiments (Section 2.2.2). Almonds were placed in a snap-cap vial filled with water, and measurements were carried out at different times during water exposure.

Images were acquired using the multi-slice multi-echo (MSME) pulse sequence (Table 1). The MSME sequence allows for the determination of $T_2 = R_2^{-1}$ values in a spatially resolved manner, with the signal decay of individual voxels fitted using a mono-exponential decay function.

3 | Results and Discussion

3.1 | Water Treatment of Almonds Monitored by MRI

In situ ^1H MRI enables direct visualization of structural changes occurring in almonds during water immersion. Experiments were performed at 20°C, 40°C, 60°C, and 80°C, and the same fundamental processes were observed at all temperatures. For clarity, the results obtained at 20°C are presented exemplarily (Figure 3). Multi-slice datasets were acquired over immersion times of up to 24 h. For analysis, a representative sagittal slice located in the center of the almond was selected, as it captures the main structural features and their temporal evolution.

At the beginning of the experiment, the T_1 -weighted images show the almond with larger signal intensity than the surrounding water, resulting in strong contrast. As immersion proceeds, a radially progressing decrease in signal intensity becomes visible, starting from the outer regions and advancing toward the center of the almond. This behavior is attributed to the inward propagation of a water front. The region in the images associated with the advancing front exhibits reduced signal intensity compared to the non-hydrated almond matrix. This fact is interpreted as a consequence of altered relaxation behavior upon water penetration. As water enters the almond tissue, the respective T_1 and/or T_2 relaxation times change, leading to a reduction in signal intensity in the T_1 -weighted images. Once the front reaches the center,

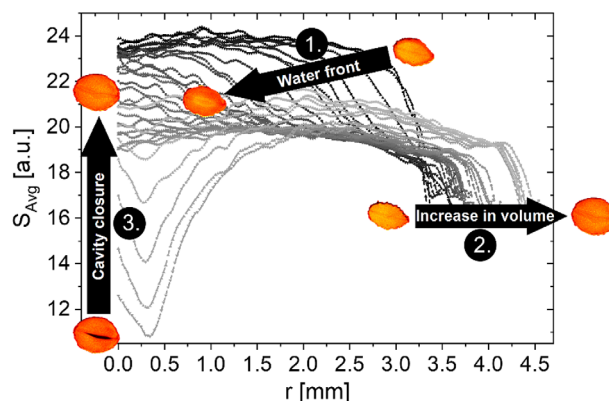


FIGURE 4 | Averaged signal intensity S_{Avg} as a function of the reduced radius r at various time points during a 24-h immersion of an almond in water. The color gradient from dark to light corresponds to early and late measurement times, respectively. These profiles were obtained using the adapted ring method [18]. Three key processes are evident in the profiles: (1) progress of the water front, visible as a sigmoidal decrease of S_{Avg} with a progressively flattening slope; (2) an increase in almond volume, indicated by the outward shift of r where S_{Avg} starts to decrease; and (3) formation and closure of an air-filled cavity, reflected by a sharp drop and subsequent recovery of S_{Avg} near the almond center. The temporal evolution of these features illustrates the structural changes during water uptake and swelling.

the almond can be considered as fully hydrated. In addition to water infiltration, pronounced swelling is observed. Initially, the almond surface exhibits a wrinkled morphology. During immersion, water initially accumulates beneath the seed coat, leading to detachment of the skin from the kernel. Subsequently, the kernel swells progressively until it fills the detached skin in the fully hydrated state. A third process is the formation of an air-filled cavity along the central axis of the almond. This cavity appears as a region with low signal intensity close to the noise level. As swelling continues, the cavity gradually closes due to expansion of the surrounding matrix. Thus, three coupled processes are consistently observed during water immersion:

1. inward propagation of a water front,
2. swelling of the almond matrix, and
3. formation of an internal cavity followed by closure.

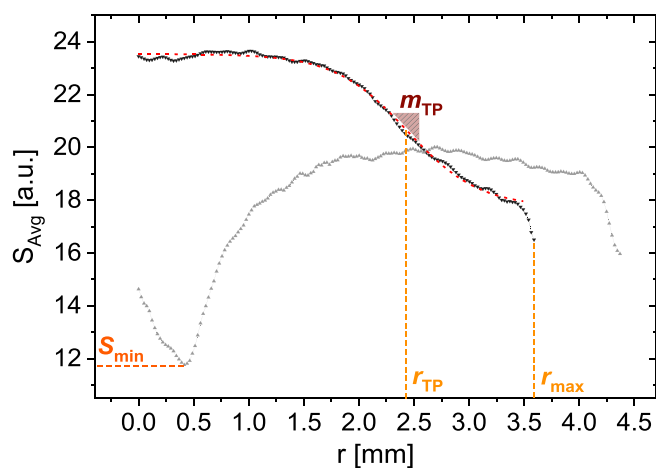


FIGURE 5 | Simplified overview showing two representative signal intensity profiles selected from the full dataset presented in Figure 4. From these profiles, key parameters are extracted to quantify the three main processes occurring during almond immersion in water: the slope at the inflection point m_{TP} of the Boltzmann function fitted to the profile (red dashed line) and the corresponding radius r_{TP} , which indicate the progression of the water front; the maximum radius r_{max} , reflecting almond swelling; and the minimum signal intensity S_{min} , serving as an indicator of cavity closure. These parameters enable a quantification of water infiltration, volume increase, and cavity formation during blanching.

To quantify these processes, the MR images were processed using the adapted ring method (Section 2.2.3). This approach yields spatially averaged signal intensity profiles $S_{Avg}(r, t)$ as a function of the reduced radius r and immersion time t . Figure 4 shows the temporal evolution of these profiles during 24 h of immersion in water at 20°C.

Three characteristic features can be identified:

1. A sigmoidal decrease in S_{Avg} associated with the water front.
2. An outward shift of the maximum radius, reflecting volume increase due to swelling.
3. A central minimum corresponding to the cavity.

To illustrate parameter extraction, two representative profiles from early and late immersion times are shown in Figure 5.

Characteristic parameters were determined from these profiles to describe the temporal evolution of each mechanism quantitatively. The following sections analyze these phenomena separately.

3.1.1 | Water Front Propagation

The progression of the water front was characterized by fitting the sigmoidal part of the radial signal intensity profiles with a Boltzmann function (Figure 5). From this fit, two parameters were extracted: the slope at the inflection point m_{TP} , describing the sharpness of the front, and the position of the inflection point r_{TP} , representing the progression of the water

front. The temporal evolution of these parameters is shown in Figure 6.

The slope m_{TP} is negative due to the representation of S_{Avg} as a function of r . With increasing time, m_{TP} approaches zero from negative values (Figure 6, left), corresponding to a gradual flattening of the sigmoidal profile as hydration progresses. The time dependence of m_{TP} is well described by an exponential function, from which a characteristic time constant $t_{m_{TP}}$ was obtained.

In contrast, the position of the inflection point r_{TP} shifts approximately linearly toward smaller radii over time (Figure 6, right). The slope of the linear fit $m_{r_{TP}}$ serves as a measure of the velocity of inward propagation of the water front.

Boltzmann fitting was only feasible up to approximately 420 min at 20°C, after which the profiles flattened due to complete hydration, and a distinct sigmoidal shape was no longer present.

3.1.2 | Increase in Volume: Swelling Dynamics

Swelling was quantified by the maximum radius r_{max} derived from the radial profiles. The increase in r_{max} over time reflects volumetric expansion of the almond during water uptake (Figure 7).

The data are best described by the sum of two sigmoidal Boltzmann functions, indicating two successive growth regimes. The characteristic parameters extracted from the fits include

1. The slopes $m_{r_{max,1}}$ and $m_{r_{max,2}}$
2. The inflection times $t_{r_{max,1}}$ and $t_{r_{max,2}}$

The first regime is attributed to rapid water accumulation beneath the skin and initial matrix expansion, whereas the second regime reflects slower structural rearrangement and equilibration within the fully hydrated matrix.

3.1.3 | Cavity Formation and Closure

Cavity dynamics were quantified using the minimum signal intensity S_{min} at the almond center. S_{min} initially decreases due to cavity formation and subsequently increases as swelling leads to closure of the cavity (Figure 8).

The temporal evolution of S_{min} can be approximated by a linear function within the observed time window. The slope $m_{S_{min}}$ serves as descriptor of the rate of cavity closure.

3.1.4 | Temperature Dependence of Characteristic Parameters

The analysis described above was performed for all investigated temperatures (20–80°C). The resulting characteristic kinetic parameters are summarized in Table 2.

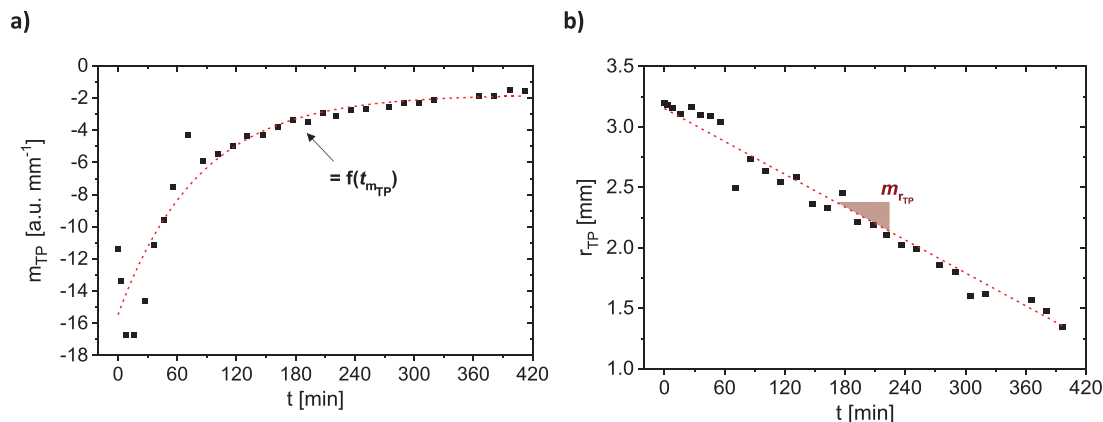


FIGURE 6 | Time parameters describing the water front inside the almond, determined from radially averaged signal intensity profiles of the MR images (Figures 4 and 5). (a) Slope at the inflection point m_{TP} of the profiles: With increasing time, m_{TP} approaches zero from negative values, corresponding to a decrease in its magnitude. The temporal evolution of m_{TP} is described by an exponential function (red dashed line), from which a characteristic time constant $t_{m_{TP}}$ is determined. (b) Position of the inflection point r_{TP} as a function of t : r_{TP} shifts toward smaller radii over time and follows a linear trend (red dashed line). The slope of the linear fit $m_{r_{TP}}$ serves as a measure of the speed of this shift. For this example of an almond immersed in water at room temperature for 24 h, the profiles can be described by a Boltzmann function up to a time of approximately 420 min.

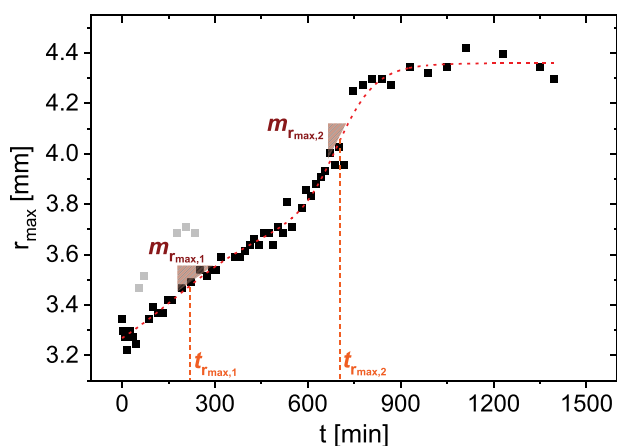


FIGURE 7 | Maximum radius r_{max} of the almond as a function of time t , determined from radially averaged signal intensity profiles of the MR images (Figures 4 and 5), describing the volumetric increase of the almond in water. The data are described by the sum of two sigmoidal Boltzmann functions (red dashed line), capturing two successive growth regimes. The corresponding slopes $m_{r_{max,1}}$ and $m_{r_{max,2}}$, as well as the times of the inflection points $t_{r_{max,1}}$ and $t_{r_{max,2}}$ of the two sigmoids, constitute characteristic parameters for quantifying the temporal evolution of r_{max} . Data points shown in light gray were identified as outliers and were not included in the fitting procedure.

When comparing the parameters across temperatures, several tendencies can be identified, although the interpretation must consider the relatively large standard deviations and the inherent biological variability of the samples.

The most consistent temperature-related trend is observed for parameters describing structural expansion. The slopes $m_{r_{max,1}}$ and $m_{r_{max,2}}$, which quantify the rate of volumetric growth, generally increase with temperature. Correspondingly, the characteristic inflection times $t_{r_{max,1}}$ and $t_{r_{max,2}}$ tend to decrease at elevated temperatures. Together, these findings indicate accelerated swelling dynamics at higher temperatures.

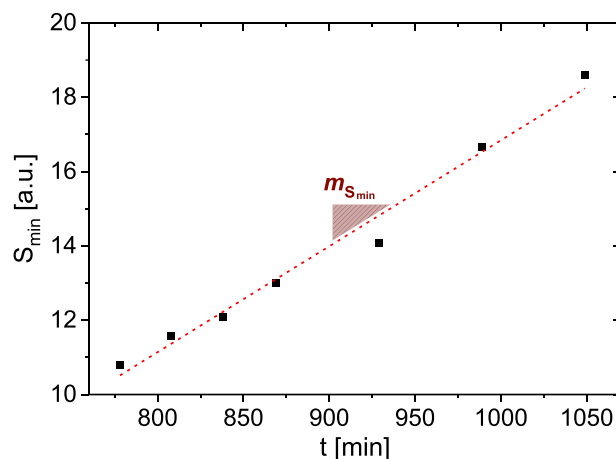


FIGURE 8 | Minimum signal intensity S_{min} as a function of time t , determined from radially averaged signal intensity profiles of the MR images (Figures 4 and 5), used to quantify cavity closure. The temporal evolution of S_{min} is described by a linear function (red dashed line). The slope of the linear fit $m_{S_{min}}$ serves as a measure of the rate of change of S_{min} .

A similar trend is observed for the apparent velocity of the water front, represented by $m_{r_{TP}}$. Although some scatter is present, the magnitude of this parameter increases at higher temperatures, suggesting faster inward propagation of hydration.

In contrast, the characteristic time constant $t_{m_{TP}}$, derived from the flattening of the sigmoidal profiles, does not exhibit a clear monotonic temperature dependence. Given its variability and the overlapping uncertainties, this parameter should not be interpreted as a robust kinetic constant. Rather, it likely reflects a combined influence of water transport, temperature-dependent relaxation behavior, and structural heterogeneity within the almond matrix.

The rate of cavity closure, quantified by $m_{S_{min}}$, could only be determined for almonds in which a clearly detectable central cavity

TABLE 2 | Characteristic parameters derived from time-resolved ^1H magnetic resonance imaging (MRI) profiles of almonds during blanching at different temperatures (20–80°C).

Parameter	Unit	20°C	40°C	60°C	80°C
Water front					
$m_{r_{TP}}$	mm min $^{-1}$	-0.005 ± 0.001	-0.003 ± 0.001	-0.009 ± 0.001	-0.010 ± 0.001
$t_{m_{TP}}$	min	84 ± 13	343 ± 176	9 ± 1	47 ± 4
Increase in volume					
$m_{r_{\max,1}}$	mm min $^{-1}$	0.003 ± 0.002	0.020 ± 0.009	0.036 ± 0.019	0.040 ± 0.012
$t_{r_{\max,1}}$	min	165 ± 92	83 ± 20	56 ± 9	46 ± 3
$m_{r_{\max,2}}$	mm min $^{-1}$	0.007 ± 0.002	0.006 ± 0.003	0.011 ± 0.005	0.024 ± 0.010
$t_{r_{\max,2}}$	min	695 ± 12	310 ± 19	176 ± 14	114 ± 27
Cavity closure					
$m_{s_{\min}}$	a.u. min $^{-1}$	0.029 ± 0.002			0.037 ± 0.003

was formed during immersion. In the present study, pronounced cavity formation and subsequent closure were observed at 20°C and 80°C, whereas at intermediate temperatures, this feature was not consistently detectable. This variability likely reflects natural variance in the internal microstructure of individual almonds, such as preexisting fissures, density variations, or differences in mechanical integrity between the two cotyledons. The formation of a central air-filled cavity appears to depend sensitively on the interplay between water uptake, matrix swelling, and internal stress redistribution. Consequently, cavity formation and closure cannot be regarded as a universal or strictly temperature-controlled phenomenon, but rather as a structural response that may occur under certain geometric and mechanical conditions. Where observable, the rate of cavity closure tends to increase at higher temperature, consistent with accelerated swelling and enhanced structural mobility of the hydrated matrix.

Overall, the temperature comparison suggests that hydration-induced structural changes in almonds are accelerated with increasing temperature. The combined analysis of water front progression, swelling behavior, and cavity evolution provides a coherent, spatially resolved picture of temperature-dependent hydration processes under conditions relevant to blanching. Due to experimental scatter and biological variability, the extracted parameters are regarded as comparative descriptors of process dynamics rather than strict material constants.

3.2 | Impact of Water Treatment on the Oleosomes on the μm -Scale

To investigate whether the swelling and structural changes observed on the millimeter to micrometer scale are accompanied by alterations on the smaller micrometer scale, integral diffusion measurements were performed using PFG-STE experiments at 400 MHz. These measurements provide information on molecular mobility within the lipid-rich almond matrix and allow insights into the microstructural organization of oil-containing compartments. The equivalent volume-weighted mean oleosome diameter $d_{33,eq}$ was determined as a function of diffusion time $\Delta = 20$ –500 ms using the Murday–Cotts model with the extension

by Packer and Rees (MCPR approach), assuming a log-normal size distribution (Figure 9).

For untreated almonds, industrially blanched almonds, and almonds self-blanched for 4 min at 80°C, $d_{33,eq}$ remains approximately constant over the investigated range of Δ . The observed Δ -independence indicates geometrically restricted diffusion within approximately spherical compartments and supports the applicability of the MCPR model under these conditions. The extracted oleosome diameters (≈ 0.8 – $1.4 \mu\text{m}$) are consistent with literature values and reflect oil stored in intact oleosomes [5, 24]. In contrast, the almond blanched for 3 h exhibits a pronounced dependence of $d_{33,eq}$ on Δ , accompanied by significantly broader σ_{MCPR} . Physically, the oleosome diameter cannot depend on Δ . In this case, the measured diffusion can no longer be described by a single population undergoing purely geometrically restricted diffusion within intact spherical compartments. After prolonged hydration, contributions from other ^1H -containing species, particularly water-associated populations, cannot be excluded.

To better understand the origin of this deviation, spectrally resolved PFG-STE data were analyzed (Figure 10).

At a diffusion time of $\Delta = 20$ ms, two spectral peaks at different chemical shifts are observed for both untreated and 3-h blanched almonds (Figure 10a,b). Due to the semisolid and heterogeneous nature of almond tissue, these broad ^1H resonances cannot be assigned unambiguously to individual molecular components. Restricted molecular mobility and dipole–dipole interactions lead to line broadening and spectral overlap between different ^1H -containing species. In liquid oils, ^1H resonances typically extend from approximately 0.9 to 5.2 ppm, whereas bulk water resonates near 4.7 ppm. Therefore, particularly the resonance in the 5–7 ppm region cannot be assigned exclusively to oil or water. A pronounced reduction of signal amplitude is already visible at low gradient amplitudes. Integration over the respective peak regions yields the diffusion-dependent signal decays (Figure 10c,d).

For the untreated almond, the signal decay is well described within the framework of restricted diffusion. In contrast, the 3-

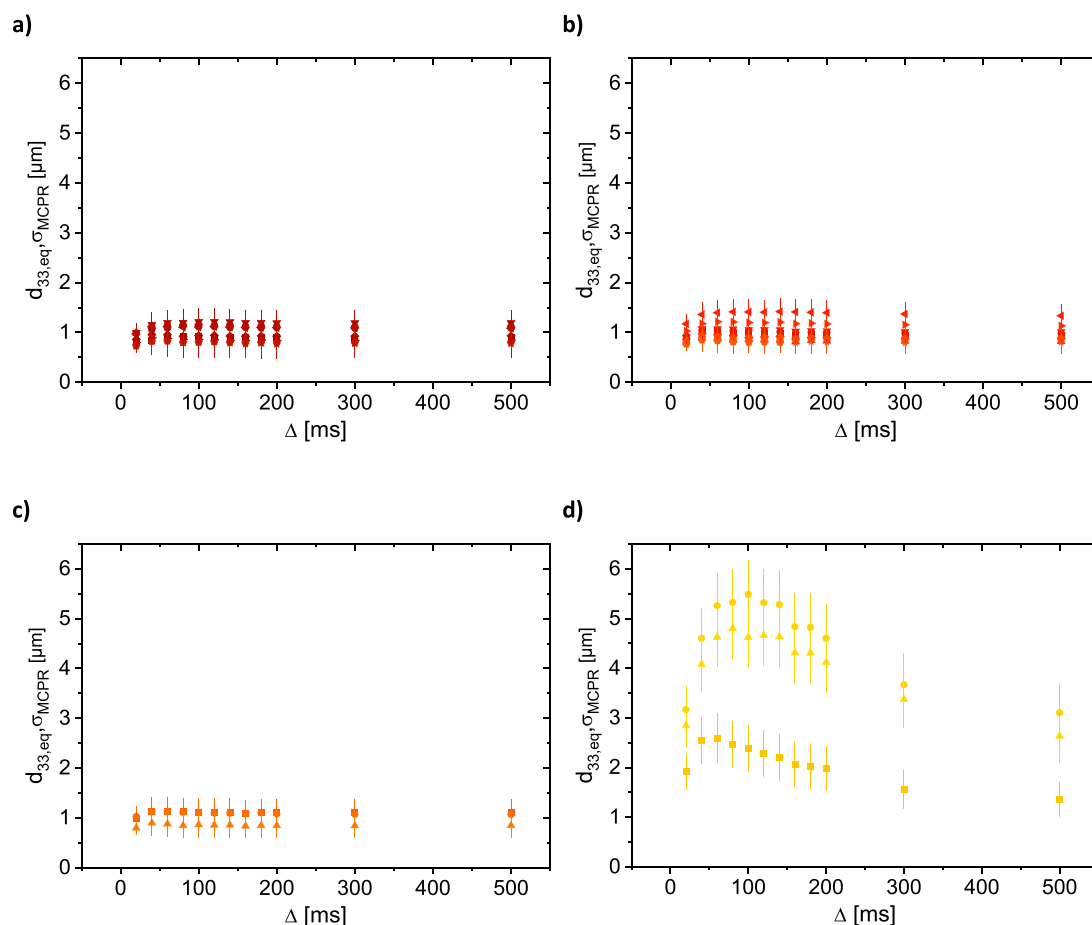


FIGURE 9 | Equivalent volume-weighted mean diameter $d_{33,eq}$ as a function of the diffusion time $\Delta = 20$ –500 ms, determined from fits of the Murday-Cotts model with the extension by Packer and Rees (MCP approach [21–24]), assuming a log-normal distribution of $d_{33,eq}$. Error bars represent the distribution width σ_{MCP} . The values are integrated over the entire spectrum for (a) 10 untreated almonds, (b) 10 industrially blanched almonds, (c) 3 self-blanched almonds (4 min at 80°C), and (d) 3 self-blanched almonds (3 h at 80°C). For the untreated, industrially blanched, and short-time self-blanched almonds, $d_{33,eq}$ remains approximately constant over the investigated range of Δ . In contrast, the almond blanched for 3 h exhibits a pronounced dependence of $d_{33,eq}$ on Δ .

h blanched almond shows a more pronounced signal decay as a function of gradient amplitude g , particularly at low q^2 values. The signal decay displays a stronger dependence on q^2 , suggesting increased effective mobility of at least part of the detected ^1H nuclear spins.

Importantly, although the diffusion experiment was initially used to investigate lipid mobility within oleosomes, the detected ^1H signal cannot be assigned exclusively to lipids. Due to the broad spectral features of almond tissue, contributions from overlapping lipid- and water-associated ^1H resonances must be considered. Prolonged blanching leads to significant swelling and water uptake, as demonstrated by the in situ MRI measurements. Water may penetrate into pores and intercellular spaces and interact with the almond matrix. Consequently, the measured PFG-STE signal may represent a superposition of contributions from lipid-associated ^1H nuclear spins within oleosomes and water-associated ^1H nuclear spins from the hydrated matrix.

If multiple components with different diffusion and relaxation properties contribute to the signal, fitting the data with a single-compartment restricted diffusion model inevitably leads to an

apparent diffusion-time dependence of $d_{33,eq}$. Therefore, the Δ -dependence observed for the 3-h blanched almonds does not necessarily imply a reduction or disappearance of oleosomes but rather indicates increased structural heterogeneity.

A unique structural interpretation cannot be derived without additional information. However, the combined NMR results suggest that prolonged water treatment modifies the microenvironment of lipids, likely as a consequence of swelling-induced matrix rearrangement and redistribution of water within the almond.

3.3 | Impact of Water Treatment on the Intrinsic Mobility in an Almond

To further disentangle geometrical restriction from intrinsic molecular mobility, transverse relaxation was investigated by CPMG experiments (Figure 11).

In both untreated and 3-h blanched almonds, two spectral peaks at different chemical shifts are observed, consistent with

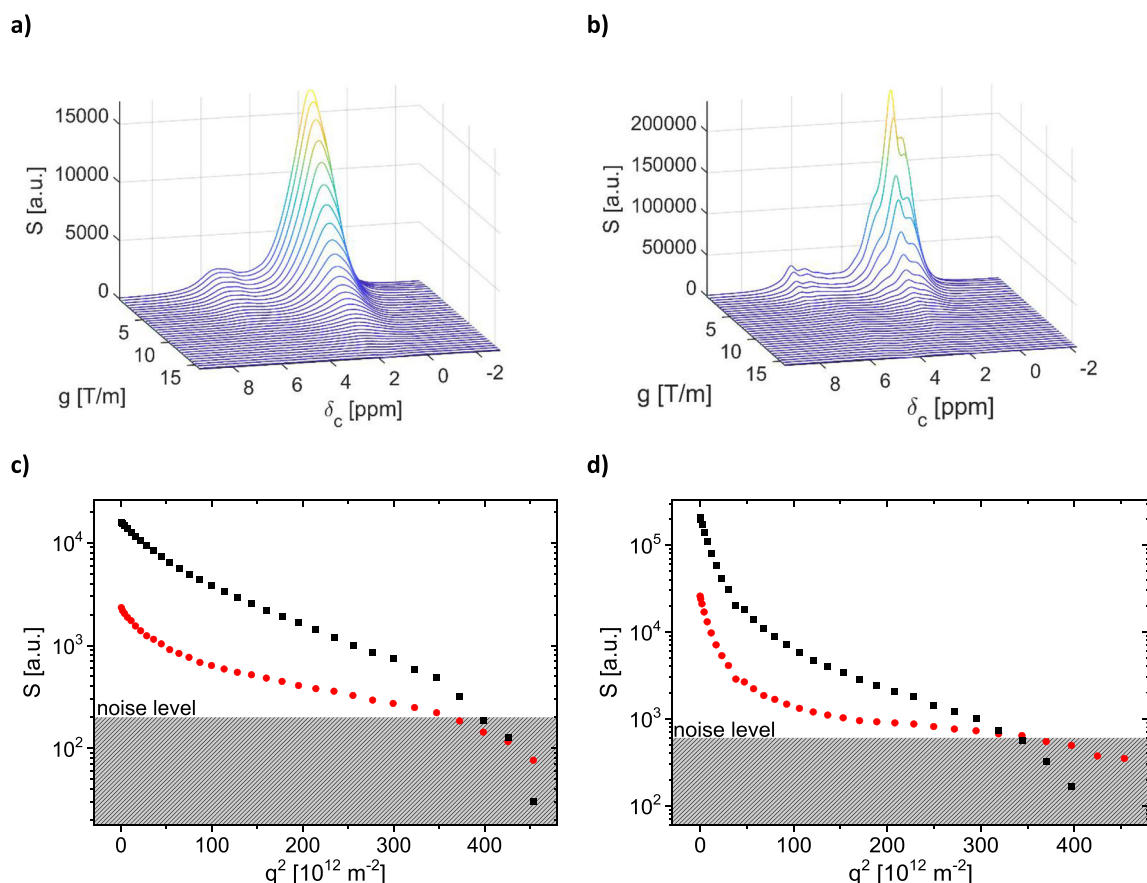


FIGURE 10 | Spectrally resolved ^1H signal decay of a PFG-STE diffusion experiment at $\Delta = 20$ ms for an (a) untreated almond and (b) almond blanched for 3 h. In both cases, two spectral peaks at different chemical shifts are observed. A pronounced reduction of the signal amplitude is already visible at low gradient amplitudes g . The spectral signatures differ slightly between the untreated and the blanched sample. Integration of the signal over the respective peak regions as a function of g yields the PFG-STE signal decays shown in (c) and (d), where black symbols correspond to the peak at 1–5 ppm and red symbols to the peak at 5–7 ppm. (c) PFG-STE signal decays for the untreated almond. (d) PFG-STE signal attenuations for the almond blanched for 3 h. The hatched area indicates the noise level. Compared to the untreated almond, the 3-h blanched almond exhibits slightly larger initial signal amplitudes and a more pronounced signal decay as a function of g .

the spectral features identified in the PFG-STE measurements (Figure 10a,b). As discussed above, the broad resonances observed in semisolid almond tissue represent overlapping contributions from different molecular environments and therefore do not allow an exclusive assignment to either water or lipid components. For the 3-h blanched almond, the peak in the 5–7 ppm region exhibits a substantially increased initial signal amplitude and contains a rapidly decaying component that is much less pronounced in untreated almonds. This indicates the presence of an additional fraction with short transverse relaxation time T_2 , suggesting altered local environments and stronger interactions with the surrounding matrix. In untreated almonds, a corresponding rapidly relaxing fraction cannot be excluded. However, due to the low native water content ($\sim 3\%$), the contribution of water-associated ^1H nuclear spins to this fraction is expected to be small. Furthermore, if present, such strongly constrained water populations are expected to exhibit very short transverse relaxation times and may therefore decay below the detection limit within the experimental window.

Importantly, due to technical constraints of the PFG-STE sequence, signal acquisition is only possible after a minimum

evolution time ($2 \cdot \tau$). Components with short T_2 relaxation times may therefore decay before contributing significantly to the diffusion measurement. As a consequence, diffusion experiments predominantly detect the longer lived fraction, whereas the short T_2 component identified in CPMG contributes only marginally. This explains the differences in signal amplitudes and decay behavior between relaxation and diffusion measurements.

This rapidly relaxing fraction in the 3-h blanched almond is consistent with the extensive swelling observed in in situ MRI experiments. Prolonged water exposure likely enhances interactions between water and the almond matrix and may create confined water populations within pores or between structures. Such water fractions exhibit reduced mobility and short T_2 , contributing to relaxation measurements while being already partially decayed in diffusion experiments.

Spatially resolved R_2 images also reveal the altered relaxation behavior upon prolonged water exposure (Figure 12).

A shift toward larger R_2 values after extended soaking indicates modified local environments and possibly mechanically induced

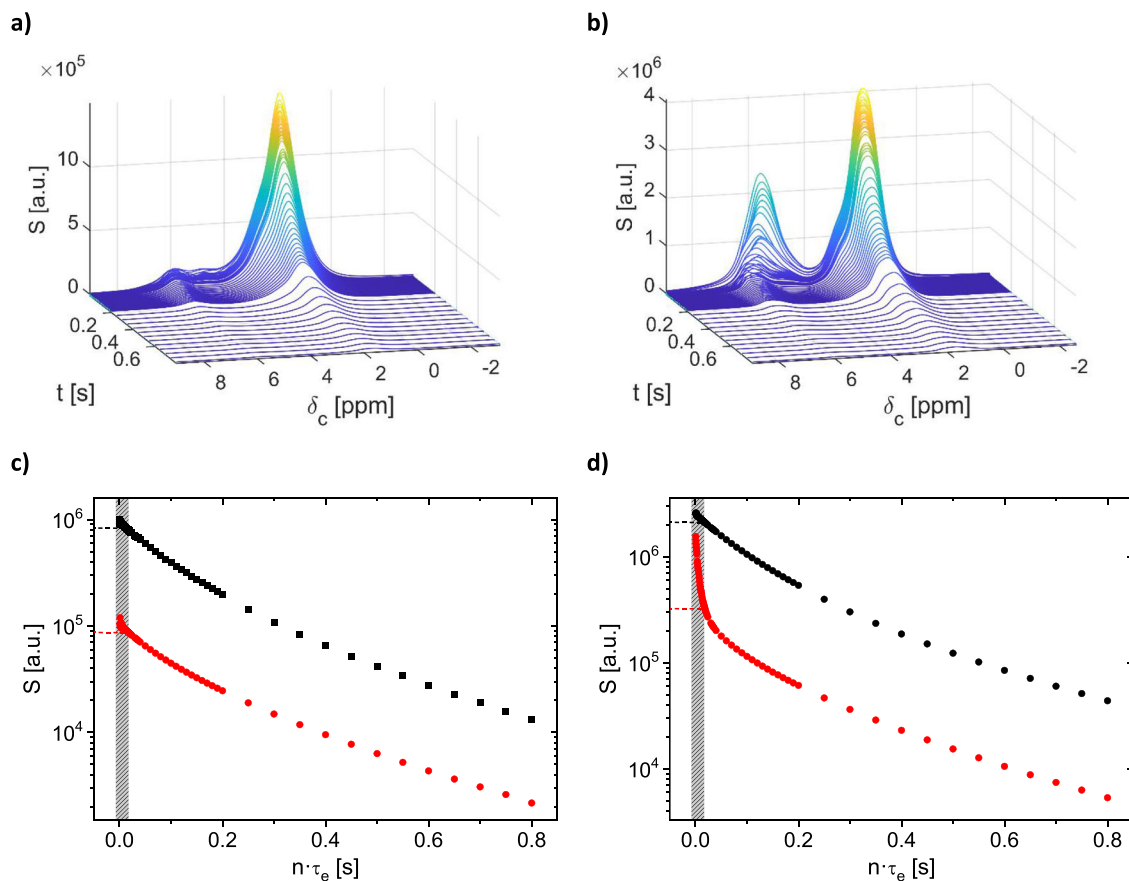


FIGURE 11 | Waterfall plots of spectrally resolved ^1H signal decay of a CPMG experiment probing intrinsic molecular mobility for an (a) untreated almond and (b) almond blanched for 3 h. In both samples, two peaks are observed. For the almond blanched for 3 h, the peak at 5–7 ppm exhibits a substantially larger initial signal amplitude compared to the untreated almond and to that of PFG-STE measurements (Figure 10a,b) and decays very rapidly. Integration over the respective peak regions as a function of $n \cdot \tau_e$ yields the CPMG signal decays shown in (c) and (d), where black symbols correspond to the peak at 1–5 ppm and red symbols to the peak at 5–7 ppm. (c) CPMG signal decays for the untreated almond. (d) CPMG signal decays for the almond blanched for 3 h. The hatched region highlights the time interval in which pronounced differences between the samples are observed. For the peak at 5–7 ppm, the signal decay of the 3-h blanched almond contains a part that decays markedly faster than in the untreated almond. The end of the hatched region marks the earliest time at which diffusion can be accessed in the PFG-STE experiments. Consequently, the rapidly relaxing component observed for the almond blanched for 3 h is not accessible in the diffusion measurements (Figure 10a,b). At longer times ($n \cdot \tau_e > 0.05$ s), the decay of the peak at 1–5 ppm and the long-time decay of the peak at 5–7 ppm are approximately parallel, indicating similar intrinsic mobility.

stresses associated with swelling. The simultaneous increase in signal amplitudes suggests chemical exchange between the almond and the surrounding water.

In summary, the ex situ diffusion and relaxation measurements indicate that short-term blanching leaves the microstructure largely unchanged compared to untreated almonds, whereas prolonged blanching induces increased structural heterogeneity. This heterogeneity likely arises from the combined effects of swelling, redistribution of water within the matrix, and modified molecular interactions, rather than from a single well-defined structural transformation of oleosomes.

4 | Conclusions

This study provides a comprehensive multiscale analysis of hydration-induced structural changes in almonds during water treatment. In situ MRI revealed temperature-dependent propaga-

tion of a water front, two-stage swelling behavior, and alterations in relaxation properties associated with matrix reorganization. Elevated temperatures significantly accelerated all processes.

Ex situ diffusion and relaxation measurements showed that short-term blanching leaves the microstructural organization of oil largely unchanged compared to untreated almonds, with diffusion behavior consistent with geometrically restricted lipids in intact oleosomes. In contrast, prolonged blanching induces increased structural heterogeneity, reflected by diffusion-time-dependent apparent diameters of oleosomes or oil compartments and the presence of rapidly relaxing components. These findings suggest enhanced water penetration, modified water–matrix interactions, and altered microenvironments rather than a single, clearly defined structural transformation of oleosomes.

In summary, the results highlight the hierarchical and temperature-dependent nature of hydration in almonds. The combination of in situ MRI and spectrally resolved diffusion

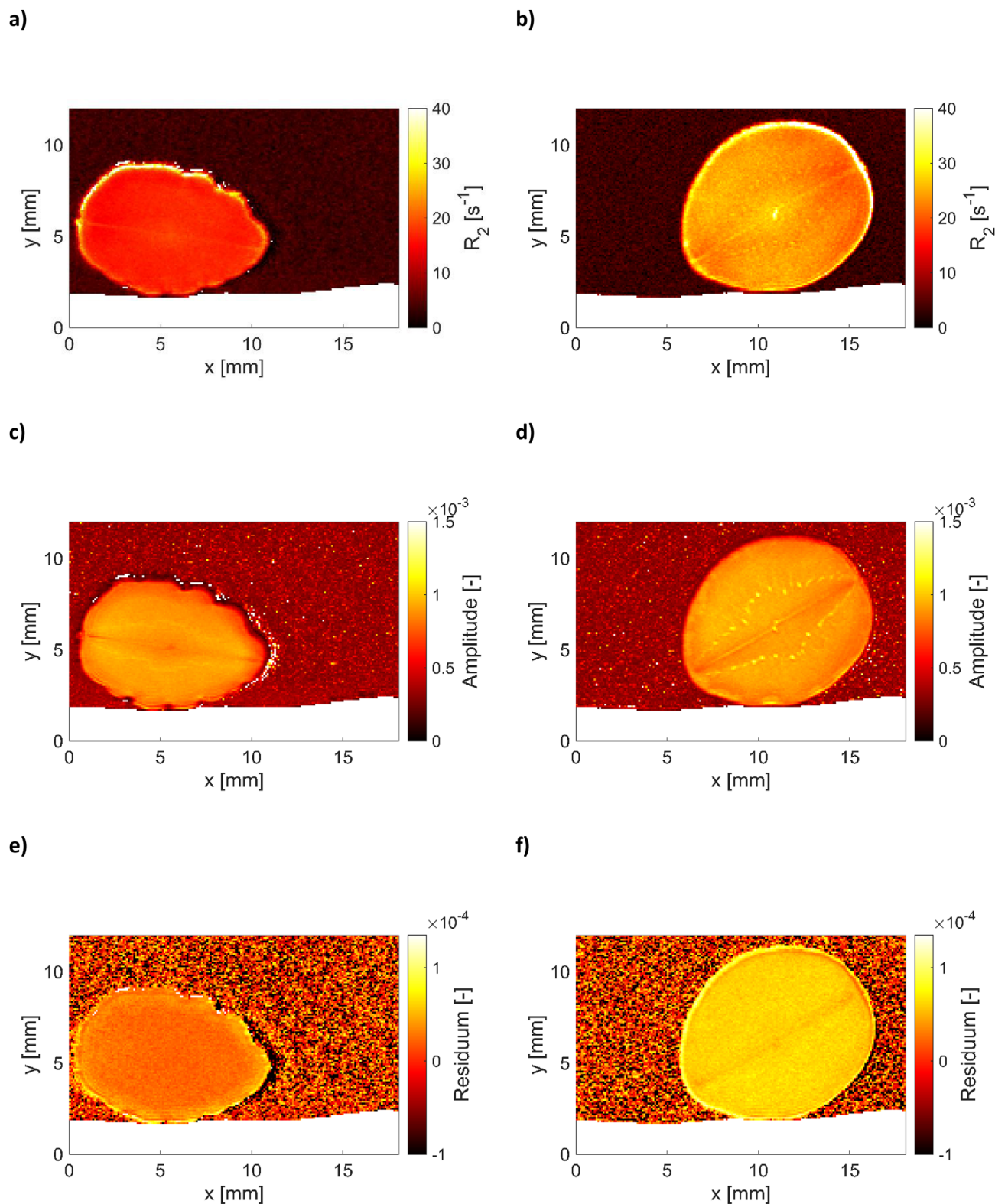


FIGURE 12 | Spatially resolved R_2 -images of an almond at room temperature immersed in water. The R_2 -images were acquired after (a) $t = 52$ min and (b) $t = 22$ h 16 min. After prolonged soaking in water, a shift toward larger R_2 is observed, indicating altered relaxation, likely caused by interactions between water and almond matrix and/or by mechanically induced stress. The images (c) and (d) show the NMR amplitudes. Slightly increased amplitudes are observed at the almond boundaries, and internal structures become more clearly visible. This suggests chemical exchange between the almond and the surrounding water, leading to an overall increase in amplitudes. The residual images (e) and (f) exhibit very small values, demonstrating that the mono-exponential fit applied voxel-wise to the measured signal decays to generate the R_2 -images provides a good description of the data.

and relaxation provides a powerful approach for linking swelling behavior to microscopic mobility and structural organization. This multiscale understanding is relevant for optimizing industrial blanching processes and for predicting texture, stability, and storage behavior of almond and nut-based products.

Author Contributions

Lena Trapp: conceptualization, methodology, software, data curation, investigation, validation, formal analysis, visualization, writing – original draft, writing – review and editing, funding acquisition, project administration. **Tanja Eirich:** writing – review and editing, writing – original draft, conceptualization, methodology, data curation, investigation, validation, formal analysis, visualization. **Hilke Schacht:** writing – review and editing, funding acquisition. **Hermann Nirschl:** supervision, funding acquisition, writing – review and editing. **Gisela Guthausen:** writing – original draft, writing – review and editing, project administration, funding acquisition, conceptualization, methodology, software, validation.

Acknowledgments

The authors thank the German Aerospace Center (DLR) for financial support of the research project IGF-Nr. 01IF23262N. This project was carried out under the auspices of DLR and financed within the budget of the Federal Ministry for Economic Affairs and Energy (BMWE) through the program to promote collective industrial research (IGF). The Deutsche Forschungsgemeinschaft is acknowledged for its substantial financial contribution in the form of NMR instrumentation and within the instrumental facility Pro²NMR. The authors also thank the Bruker BioSpin GmbH μ -imaging application group for their support and Richard von Budberg for manufacturing the glass apparatus.

Open access funding enabled and organized by Projekt DEAL.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. M. Fisklements and D. M. Barrett, “Kinetics of Almond Skin Separation as a Function of Blanching Time and Temperature,” *Journal of Food Engineering* 138 (2014): 11–16, <https://doi.org/10.1016/j.jfoodeng.2014.03.012>.
2. M. M.-L. Grundy, K. Lapsley, and P. R. Ellis, “A Review of the Impact of Processing on Nutrient Bioaccessibility and Digestion of Almonds,” *International Journal of Food Science & Technology* 51 (2016): 1937–1946, <https://doi.org/10.1111/ijfs.13192>.
3. C. A. Hughey, R. Januszewicz, C. S. Minardi, et al., “Distribution of Almond Polyphenols in Blanch Water and Skins as a Function of Blanching Time and Temperature,” *Food Chemistry* 131 (2012): 1165–1173, <https://doi.org/10.1016/j.foodchem.2011.09.093>.
4. F. Beisson, N. Férté, S. Bruley, R. Vouloutoury, R. Verger, and V. Arondel, “Oil-Bodies as Substrates for Lipolytic Enzymes,” *Biochimica et Biophysica Acta (BBA)—Molecular and Cell Biology of Lipids* 1531 (2001): 47–58.
5. R. Perren, *Untersuchungen über Das Rösten von Haselnüssen*. PhD Thesis (ETH Zürich, 1995).
6. O. A. Karkani, N. Nenadis, C. V. Nikiforidis, and V. Kiosseoglou, “Effect of Recovery Methods on the Oxidative and Physical Stability of Oil Body Emulsions,” *Food Chemistry* 139 (2013): 640–648, <https://doi.org/10.1016/j.foodchem.2012.12.055>.
7. S. Gallier, K. C. Gordon, and H. Singh, “Chemical and Structural Characterisation of Almond Oil Bodies and Bovine Milk Fat Globules,” *Food Chemistry* 132 (2012): 1996–2006, <https://doi.org/10.1016/j.foodchem.2011.12.038>.
8. C. V. Nikiforidis, A. Matsakidou, and V. Kiosseoglou, “Composition, Properties and Potential Food Applications of Natural Emulsions and Cream Materials Based on Oil Bodies,” *RSC Advances* 4 (2014): 25067–25078, <https://doi.org/10.1039/C4RA00903G>.
9. E. A. Decker and P. Villeneuve, “Impact of Processing on the Oxidative Stability of Oil Bodies,” *Critical Reviews in Food Science and Nutrition* 64 (2024): 6001–6015, <https://doi.org/10.1080/10408398.2022.2160963>.
10. K. W. Smith, F. W. Cain, and G. Talbot, “Effect of Nut Oil Migration on Polymorphic Transformation in a Model System,” *Food Chemistry* 102 (2007): 656–663, <https://doi.org/10.1016/j.foodchem.2006.05.045>.
11. K. W. Smith, I. Zand, and G. Talbot, “Effect of Antibloom Fat Migration From a Nut Oil Filling on the Polymorphic Transformation of Cocoa Butter,” *Journal of Agricultural and Food Chemistry* 56 (2008): 1602–1605, <https://doi.org/10.1021/jf072151s>.
12. N. Bernat, M. Chafer, J. Rodríguez-García, A. Chiralt, and C. González-Martínez, “Effect of High Pressure Homogenisation and Heat Treatment on Physical Properties and Stability of Almond and Hazelnut Milks,” *LWT—Food Science and Technology* 62 (2015): 488–496, <https://doi.org/10.1016/j.lwt.2014.10.045>.
13. S. Dhakal, M. M. Giusti, and V. Balasubramaniam, “Effect of High Pressure Processing on Dispersive and Aggregative Properties of Almond Milk,” *Journal of the Science of Food and Agriculture* 96 (2016): 3821–3830, <https://doi.org/10.1002/jsfa.7576>.
14. L. Trapp, N. Weis, N. Karschin, H. Schacht, H. Nirschl, and G. Guthausen, “Processes of Thermal Treatment on Hazelnuts Investigated by NMR and MRI,” *Magnetic Resonance in Chemistry* 64 (2026): 427–437, <https://doi.org/10.1002/mrc.70084>.
15. C. S. Ulrich Tietze and E. Gamm, *Electronic Circuits—Handbook for Design and Application*, p. XLVI (Springer Berlin, Heidelberg, 2008).
16. J. Hennig, A. Nauerth, and H. Friedburg, “RARE Imaging: A Fast Imaging Method for Clinical MR,” *Magnetic Resonance in Medicine* 3 (1986): 823–833, <https://doi.org/10.1002/mrm.1910030602>.
17. J. M. Pope, “Quantitative NMR Imaging of Flow,” *Concepts in Magnetic Resonance* 5 (1993): 281–302, <https://doi.org/10.1002/cmr.1820050402>.
18. N. Schork, S. Schuhmann, H. Nirschl, and G. Guthausen, “In Situ Measurement of Deposit Layer Formation During Skim Milk Filtration by MRI,” *Magnetic Resonance in Chemistry* 57 (2019): 738–748, <https://doi.org/10.1002/mrc.4826>.
19. J. E. Tanner and E. O. Stejskal, “Restricted Self-Diffusion of Protons in Colloidal Systems by the Pulsed-Gradient, Spin-Echo Method,” *Journal of Chemical Physics* 49 (1968): 1768–1777, <https://doi.org/10.1063/1.1670306>.
20. R. M. Cotts, M. J. R. Hoch, T. Sun, and J. T. Markert, “Pulsed Field Gradient Stimulated Echo Methods for Improved NMR Diffusion Measurements in Heterogeneous Systems,” *Journal of Magnetic Resonance* 83 (1989): 252–266.
21. J. S. Murday and R. M. Cotts, “Self-Diffusion Coefficient of Liquid Lithium,” *Journal of Chemical Physics* 48 (1968): 4938–4945, <https://doi.org/10.1063/1.1668160>.
22. C. H. Neuman, “Spin Echo of Spins Diffusing in a Bounded Medium,” *Journal of Chemical Physics* 60 (1974): 4508–4511, <https://doi.org/10.1063/1.1680931>.
23. K. J. Packer, D. J. Tomlinson, and C. Rees, “Studies of Diffusion and Flow by Pulsed NMR Techniques,” *Advances in Molecular Relaxation Processes* 3 (1972): 119–131, [https://doi.org/10.1016/0001-8716\(72\)80029-4](https://doi.org/10.1016/0001-8716(72)80029-4).
24. L. Trapp, H. Schacht, H. Nirschl, and G. Guthausen, “Oleosomes in Almonds and Hazelnuts: Structural Investigations by NMR,” *Frontiers in Physics* 13 (2025): 1494052, <https://doi.org/10.3389/fphy.2025.1494052>.

25. H. Y. Carr and E. M. Purcell, "Effects of Diffusion on Free Precession in Nuclear Magnetic Resonance Experiments," *Physical Review* 94 (1954): 630–638, <https://doi.org/10.1103/PhysRev.94.630>.
26. S. Meiboom and D. Gill, "Modified Spin-Echo Method for Measuring Nuclear Relaxation Times," *Review of Scientific Instruments* 29 (1958): 688–691, <https://doi.org/10.1063/1.1716296>.