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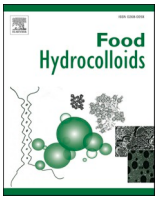

New opportunity of using pulsed electric field (PEF) technology to produce texture-modified chickpea flour-based gels for people with dysphagia

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ABSTRACT

An aging population has driven a need for novel food products that are dysphagia-friendly but still provide adequate nutrition. This study investigated the potential of pulsed electric field (PEF) processing to create gels with varied textures from a chickpea flour slurry (10 % w/w). PEF treatment at 1 or 2 kV/cm and 410–500 kJ/kg induced the formation of soft gels after overnight cooling (24 h, 4 °C). As specific energy increased, the hardness of the gels rose (0.35 ± 0.01 to 2.94 ± 0.19 kPa), along with notable increases in rheological properties, including storage modulus (195 ± 42 to 2350 ± 466 Pa) and yield stress (5.7 ± 5.6 to 423.4 ± 135.2 Pa) of the gels, with textures spanning a range of International Dysphagia Diet Standardisation Initiative levels. However, no differences in these parameters were observed between the two field strengths. Fourier transform infrared spectra and light microscopy revealed that gel formation was mainly attributed to starch gelatinisation (1047/1021 ratio decreased from 0.759 ± 0.007 to 0.699 ± 0.002) caused by a temperature increase due to the Joule effect during PEF, while protein denaturation and aggregation became important in PEF-treated chickpea slurries above 450 kJ/kg, resulting in a more solid-like gel formation. Importantly, gels formed following treatment at 2 kV/cm led to an increase in readily digestible starch (16.28 ± 0.15 to 89.06 ± 1.78 %) and a faster intestinal protein digestion rate (1.16 ± 0.20 × 10^{-2} to 1.65 ± 0.04 × 10^{-2} min^{-1}) during simulated gastrointestinal digestion. This study demonstrated the use of PEF treatment as a rapid method (44.4–227.4 ms) to produce gels with varying textural and rheological consistencies using a single ingredient, e.g. chickpea flour.

1. Introduction

As the world population continues to age, its food-related needs also change. This trend is already observable in most countries, especially those with a higher average age. Older adults tend to suffer more frequently from sensory impairments and swallowing difficulties, conditions that require the development of specifically tailored food products (Khan et al., 2014). Among these conditions, oropharyngeal dysphagia (OD) is one of the most common, with incidences up to 30 % in healthy elderly patients (Ribeiro et al., 2024). Moreover, OD can arise from other conditions such as stroke and oral cancer, which in turn affects the patient's proper hydration and nutrition and increases the risk of aspiration pneumonia (Altman et al., 2010).

A growing research effort is focusing on understanding the proper textural and rheological properties that foods must meet for this specific population segment. This challenge is made even more complex by the nature of the swallowing process itself, comprising different forces, such as shearing and elongational forces, that act on the food as it travels from the mouth to the stomach (Gallegos et al., 2023). Broadly speaking, OD-affected patients can suffer from reduced tongue control, thus increasing viscosity may be helpful to improve "in-mouth" food control. On the other hand, excessive gel hardness can pose challenges for people with chewing difficulties or swallowing pain, thus tenderisation or food mincing may improve food intake. Various techniques such as the International Dysphagia Diet Standardisation Initiative (IDDSI) and the National Dysphagia Diet task force (NDD) have been developed to

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characterise the consistency of food products and facilitate the provision of texture and viscosity appropriate to patients with swallowing difficulties (Cichero et al., 2017; National Dysphagia Diet Task Force & American Dietetic Association, 2002). These techniques have been useful to establish baseline information to ensure foods designed for dysphagia patients exhibit desirable textures, which may help to promote adequate oral intake, thus supporting nutrition. However, while IDDSI and NDD techniques are both assessable and simple to perform, they do not offer a comprehensive and reliable characterisation provided by more advanced techniques such as videofluoroscopic swallow studies (Brito-de la Fuente et al., 2012). Indeed, such *in vivo* studies are considered physiologically relevant, as they account for dynamic factors during the actual food consumption, including the tongue handling, the act of swallowing itself, together with the action of endogenous enzymes such as salivary amylases, all of which can significantly alter the rheological properties of the food bolus and thus the consumption applicability and safety for OD patients (Gallegos et al., 2023; Ortega et al., 2020).

Nevertheless, many approaches have already been attempted to obtain foods with specific texture, such as the use of thickeners, different tenderisation techniques or specific product formulations (Methacanon et al., 2021; Pematilleke et al., 2024). The application of emerging processing technologies, such as ultrasound, 3D printing and high-pressure processing, have also been investigated due to their possible advantages, including enhanced personalisation of food products and texture softening without significant nutrient losses or dilution (Bhuiyan et al., 2024, 2025; Liu et al., 2024; Sungsinchai et al., 2019).

Pulsed electric fields (PEF) is a technology based on the delivery of short (μs-ms), high voltage pulses of current through a conductive medium, creating an electric field. It is often utilised in the food industry for applications involving mass transfer, where the application of electric fields above a critical value can induce cell membrane permeabilisation, thus enhancing the mass transfer process (Donsì et al., 2010; Karki et al., 2022). More recently, the use of PEF on products where intact cell membranes are absent or damaged (e.g. flours or protein isolates) has been investigated as a tool to improve technological properties, focusing on the possible effects on structure modification of macromolecules such as starch and proteins (Giteru et al., 2018). The underlying mechanisms in this application, though not fully understood, are thought to involve structural stretching and reorganisation due to the polarisation force of the electric field on charged structures, as well as electrochemical reactions like charged particle and radical formation from water hydrolysis near electrode surfaces (Giteru et al., 2018; Milanezzi & Silva, 2025). However, increasing specific energy will inevitably produce more heat due to the Joule effect, thus temperature-mediated changes may also occur.

Most studies apply electric fields above 10 kV/cm, particularly when used for pasteurisation. However, some studies have found that lower electric fields (<5 kV/cm) could result in structural modification of flours, such as cassava (Conde et al., 2022), wheat (Achayuthakan et al., 2023) and oat (Duque et al., 2020b) or on protein isolates (Gulzar et al., 2024) and concentrates (Melchior et al., 2020). The use of low electric fields has been reported to result in limited protein structural modification (Taha et al., 2022) which implies better retention of nutritional value. Moreover, from an industrial point of view, PEF treatment at low electric fields on semi-solid foods (including slurries) is more favourable due to the lower cost of generators and reduced energy consumption compared to high electric field applications. Although some structural effects have been observed for both starch and protein, there is less agreement regarding the impact on functional properties, where other factors (e.g. particle size) could play a role. Given that the production of dysphagia-friendly products can be mediated through either protein gelation or starch gelatinisation, it is important to understand the effect of PEF treatment on the functional properties of protein and starch, particularly when present as mixtures.

Legumes, such as chickpeas, are a promising ingredient for developing dysphagia-friendly gels due to their high protein and carbohydrate content. Although legumes generally contain higher levels of antinutritional factors compared to cereals, they are rich in fibre and are often less allergenic for certain population groups such as individuals with celiac disease (Grasso et al., 2022; Kaur & Prasad, 2021). Among legumes, chickpeas are the second most widely produced pulse globally, with India being the leading producer (FAO, 2025). Moreover, their relatively higher fat content compared to other legumes (except for soybeans) makes them a nutritionally balanced ingredient for food formulation (Jukanti et al., 2012). Furthermore, the widespread use of its flour for various product formulations presents a promising starting point for chickpea flour as the main ingredient for dysphagia-designed food products.

To the best of our knowledge, there are no studies investigating the effect of PEF on legume flour gelation, particularly in a slurry form. Therefore, the aim of this study was to assess the feasibility of using PEF treatment at different electric field strengths and specific energy levels on a chickpea flour slurry to produce gels with specific textural and rheological characteristics. Moreover, selected analyses were conducted to investigate the underlying mechanisms of gel formation induced by PEF treatment.

2. Materials and methods

2.1. Chickpea and chemical reagents

Chickpea flour was acquired from a local supplier (Lot. NZ034699, Scalzo Foods Industries, Melbourne, Australia) and stored in airtight plastic bags until use. The proximate composition of the flour was determined (in triplicate) as follows: moisture 8.70 ± 0.27 % (AOAC 14.004), crude protein 22.24 ± 0.19 % (AOAC 14.067, nitrogen × 6.25), crude fat 5.74 ± 0.13 % (AOAC 14.018), ash 2.20 ± 0.08 % (AOAC 14.006), starch 42.94 ± 2.03 % (Megazyme AA/AMG kit, Wicklow, Ireland) and non-starch carbohydrates 18.32 % (calculated by difference). For in vitro digestion, the following enzymes were used: *Aspergillus oryzae* α-amylase (Sigma 10065, St. Louis, Missouri, USA), porcine stomach pepsin (A4289, AppliChem, Darmstadt, Germany), porcine pancreas pancreatin (Sigma P7545) and porcine bile extract (SC-214601, ChemCruz, Dallas, Texas, USA).

2.2. PEF treatments

Chickpea flour and distilled water were weighed (PBC 3500, Kern, Albstadt, Germany) in individual screw cups to obtain 100 g slurry with a flour concentration of 10 ± 0.01 % (wet basis, wb) and electrical conductivity of 2.15 ± 0.08 mS/cm. To ensure flour hydration, all slurries were left to hydrate at 3.1 ± 0.6 °C for 16 h prior to PEF treatment. A 10 % concentration was selected based on preliminary trials, as lower concentrations did not lead to gelation while highly concentrated mixtures resulted in excessive electrical conductivity, which hindered the operation and performance of the PEF unit system used in this study.

PEF treatments were performed using a pilot scale PEF system (ELCRACK-HVP 5, DIL, Quakenbrueck, Germany) operated in batch mode using a chamber (10 cm length and 5 cm depth) with an 8 cm stainless-steel electrode gap. The system delivered bipolar square pulses with a constant pulse duration of 30 μs and frequency of 200 Hz, monitored through an oscilloscope (UT2025C, Uni-Trend, Dongguan, China). For each treatment, the slurry was gently shaken in the screw cup and transferred into the chamber (average treatment mass 98.41 ± 0.22 g). The sample temperature was then manually measured using a digital thermometer (Temp10K, Thermo Scientific, Waltham, Massachusetts, USA) placed at the centre of the treatment chamber. PEF treatment was immediately performed to minimise temperature changes and prevent sedimentation. Following PEF treatment, the sample temperature was measured within 30 s after the delivery of the final pulse. It

is acknowledged that some heat dissipation to the environment likely occurred during the PEF treatment and the brief interval before measurement, resulting in recorded temperatures being slightly lower than the actual peak temperatures achieved during treatment.

Based on preliminary trials, two electric field strengths (1 and 2 kV/cm) were selected, based on the conductivity of the sample and the maximum current (100 A) that could be applied using said PEF generator. The application of PEF at specific energies exceeding 500 kJ/kg resulted in an in-chamber starch gelatinisation, producing strong gels that could not be poured and formed undesirable clumps. Conversely, PEF application at energies below 410 kJ/kg failed to form gels, with sedimentation observed over time, similar to what was observed in control samples. Based on these observations, PEF treatments within the range of 410–500 kJ/kg were selected for further evaluation of their ability to induce the formation of chickpea gels. A sampling interval of 15–20 kJ/kg was chosen to provide adequate resolution for monitoring structural changes, while ensuring that the energy levels were achievable within the current experimental setup. The number of pulses and pulse energy were used to calculate the specific energy applied to a certain sample weight. To ensure consistency across replications, the same pulse number was used to achieve certain target energy values. However, minor variations in pulse energy and sample weight influenced the resulting specific energy. Therefore, the energy levels reported in this study represent the best attempts to cover the targeted specific energy range. The exact specific energy values delivered in each treatment are detailed in Table 1, while the rounded values of 410, 425, 450, 465, 485 and 500 kJ/kg are used for simplicity and ease of discussion.

2.3. Setting of PEF-produced chickpea gels

Following PEF treatment, each chickpea slurry in the PEF chamber was quickly mixed with a plastic spatula and transferred to a 100 mL plastic container (5 cm height, 6 cm diameter) to allow gel setting for 24 h under refrigerated conditions (4 °C) (Fisher & Paykel, Auckland, New Zealand). A total of 10 chickpea gels were prepared for each PEF treatment. Chickpea flour-water slurries without PEF treatment (later referred to as “untreated”) were used as control.

2.4. Classification of PEF-produced chickpea gels using the International Dysphagia Diet Standardisation Initiative (IDDSI) framework

To classify the obtained chickpea gels using the 8-scale level under the IDDSI framework, the fork-press, fork-drip and spoon-tilt tests were performed in accordance with IDDSI methodology (Cichero et al., 2017; Xie et al., 2024) on five different gel samples for each PEF treatment condition. Briefly, under the framework, levels 0 to 2 refer to liquid food with increasing thickness, levels 3 and 4 indicate intermediate consistencies between liquid and solid, while levels 5 to 7 refer to solid foods. Photos of the gels were simultaneously captured in a standardised manner using an iPhone 13 (Apple Inc., Cupertino, California, USA) mounted on a fixed stand 40 cm in front of the sample with camera settings of 1/16 aperture and 1/100 s shutter speed.

2.5. Texture analysis of PEF-produced chickpea gels

Compression tests were performed on chilled (4 °C) chickpea gels (from Section 2.3) in their own container using a texture analyser (TA. HDplus, TA Stable Microsystems, Surrey, UK) equipped with a 5 kg load cell and a 20 mm cylindrical probe (P/20). Compression was conducted at a probe speed of 0.5 mm/s until 60 % strain was reached, with a trigger force of 0.01 N. Hardness was measured as the maximum stress recorded, while Young’s modulus was calculated as the slope of the curve until 5 % strain on a stress-strain plot, using the instrument software (Exponent, TA Stable Microsystems, Surrey, UK). Texture analysis was repeated on five independent chickpea gel samples for each condition. To better highlight the effect of specific energy, obtained data were fitted to an exponential equation regardless of the voltage used. After texture analysis, the gel samples were freeze-dried (FreeZone Plus, Labcono, Kansas City, Missouri, USA) for subsequent FTIR and DSC analysis.

2.6. Rheological assessment of PEF-produced chickpea gels

2.6.1. Flow behaviour

Flow curve was carried out at 25 °C using a rheometer (Discovery HR-3, TA Instruments, New Castle, Delaware, USA) equipped with a 40 mm parallel plate geometry and 1 mm gap. Flow behaviour was performed after the gel sample (from Section 2.3) had rested for 3 min to allow structural relaxation after loading. The shear rate was varied from 0.1 to 100 s^{-1}, and the test was conducted in triplicate. To better highlight the effect of specific energy, data at 50 s^{-1} were fitted to a linear equation irrespective of the voltage used. To avoid misinterpretation, rotational data were used solely to discuss the differences between IDDSI and NDD classification in the current study, while the

Table 1
PEF process parameters used to treat chickpea slurry samples (mean ± standard deviation, $n = 10$).

Sample code[a]	Electric field strength [kV/cm]	Specific energy [kJ/kg]	Pulse count	Average pulse energy [J]	Treatment time [ms]	Electrical resistance[b] [Ω]	Delta temperature[c] [°C]
1_500	1.05 ± 0.00^{e}	501.4 ± 2.06^{a}	7579 ± 19^{a}	6.5 ± 0.02^{d}	227.4 ± 0.56^{a}	146 ± 1.03^{e}	66.5 ± 0.98^{ab}
1_485	1.04 ± 0.02^{e}	485.4 ± 2.64^{b}	7346 ± 33^{b}	6.5 ± 0.03^{d}	220.4 ± 1.00^{b}	149 ± 1.88^{d}	65.7 ± 2.10^{b}
1_465	1.05 ± 0.01^{e}	469.6 ± 3.69^{c}	7133 ± 45^{c}	6.5 ± 0.03^{d}	214.0 ± 1.35^{c}	152 ± 1.50^{c}	63.6 ± 1.36^{c}
1_450	1.05 ± 0.00^{e}	449.3 ± 1.77^{e}	6846 ± 8^{d}	6.5 ± 0.02^{d}	205.4 ± 0.25^{d}	155 ± 0.99^{b}	60.5 ± 1.57^{d}
1_425	1.05 ± 0.02^{e}	429.8 ± 1.87^{g}	6590 ± 21^{e}	6.4 ± 0.02^{e}	197.7 ± 0.63^{e}	160 ± 1.08^{a}	57.8 ± 0.90^{e}
1_410	1.05 ± 0.00^{e}	411.9 ± 1.31^{hi}	6343 ± 19^{f}	6.4 ± 0.00^{e}	190.3 ± 0.57^{f}	164 ± 1.07^{a}	56.5 ± 0.53^{fg}
2_500	2.02 ± 0.03^{d}	500.6 ± 3.16^{a}	1794 ± 9^{g}	27.5 ± 0.15^{a}	53.8 ± 0.26^{g}	140 ± 2.45^{f}	67.3 ± 1.35^{a}
2_485	2.05 ± 0.05^{c}	485.7 ± 5.72^{b}	1738 ± 18^{h}	27.5 ± 0.24^{a}	52.1 ± 0.53^{h}	145 ± 5.49^{e}	64.3 ± 1.23^{c}
2_465	2.06 ± 0.04^{bc}	464.4 ± 3.23^{d}	1665 ± 12^{i}	27.5 ± 0.10^{ab}	50.0 ± 0.36^{i}	148 ± 3.39^{d}	61.0 ± 1.60^{d}
2_450	2.08 ± 0.03^{ab}	447.2 ± 5.06^{f}	1604 ± 20^{j}	27.4 ± 0.10^{b}	48.1 ± 0.60^{j}	151 ± 2.70^{c}	57.6 ± 2.24^{ef}
2_425	2.08 ± 0.03^{ab}	424.3 ± 2.47^{h}	1535 ± 2^{k}	27.2 ± 0.12^{c}	46.1 ± 0.07^{k}	154 ± 2.29^{b}	55.6 ± 1.36^{gh}
2_410	2.09 ± 0.02^{a}	409.4 ± 3.96^{i}	1479 ± 2^{l}	27.2 ± 0.17^{c}	44.4 ± 0.06^{l}	156 ± 4.59^{b}	53.7 ± 1.93^{h}

Different letters within the same column indicate statistically significant differences ($p < 0.05$).
Fixed PEF and sample parameters were as follows: frequency 200 Hz, pulse length 30 μs, bipolar square pulses, initial temperature of the sample 3.1 ± 0.6 °C and sample conductivity 2.15 ± 0.08 mS/cm.

[a] Sample codes represent the two process variables: electric field strength and specific energy.

[b] The electrical resistance of the sample in the PEF chamber was estimated by the PEF interface software based on the actual electric current and voltage delivered through the sample.

[c] The delta temperature was estimated based on the difference between the temperature of the sample measured 30 s after the last PEF pulse delivered and the initial temperature of the sample measured 30 s before the first PEF pulse delivered.

primary rheological discussion focused on oscillatory data.

2.6.2. Amplitude sweep

Using the same rheometer set up, elastic modulus (G′) and loss modulus (G′′) were recorded over a logarithmic amplitude ramp from 0.1 to 1000 % at a fixed frequency of 0.1 Hz. The test was conducted in triplicate on freshly loaded samples (from Section 2.3) for each PEF treatment condition. The limit for the linear viscoelastic region (LVR), and yield stress (extrapolated from the stress-strain plot) were calculated using the TRIOS software (TA Instruments, New Castle, Delaware, USA). To better highlight the effect of specific energy, yield stress data were fitted to a linear equation irrespective of the voltage used.

2.6.3. Frequency sweep

Finally, freshly loaded chickpea gel samples (from Section 2.3) for each PEF treatment condition, were analysed in triplicate performing a frequency sweep test after 3 min of resting, ranging from 0.01 to 100 Hz. G′, G′′ and tan δ were recorded. Amplitude values were chosen to ensure the test was conducted within the LVR for each gel sample. The G′ and G′′ curves were fitted using the following Power Law equations (Eqs. 1 and 2) using TRIOS software.

$$G' = A' \cdot \omega^{B'} \quad \text{Eq. (1)}$$

$$G'' = A'' \cdot \omega^{B''} \quad \text{Eq. (2)}$$

where ω represents the angular frequency (rad/s), while A′, A′′ are the constants and B′, B′′ the exponential factors for the equations. To better highlight the effect of specific energy, A′ data were fitted to a linear equation irrespective of the voltage used.

2.7. Evaluation of syneresis and soluble protein leaching from PEF-produced chickpea gels

Immediately after the PEF treatments, chickpea slurry samples were transferred to four pre-weighed 50 mL falcon tubes, and the initial weights were recorded. After 24 h of refrigerated storage (4 °C), the gel samples were centrifuged at 4500 × *g* for 10 min (Kubota 7000, Tokyo, Japan), and the supernatant was collected and weighed. Syneresis was calculated by dividing the supernatant weight by the initial slurry sample weight and expressed as a percentage (Bashir & Aggarwal, 2016). Samples treated with 410 kJ/kg were not assessed for syneresis and protein leaching due to their extremely weak structure which challenged appropriate separation of the supernatant from the gel. The amount of protein leached into the supernatant was determined using the Bradford method (Bradford, 1976) in a 96-well plate, with absorbance measured at 595 nm using a plate reader (Synergy 2, BioTek, Winooski, Vermont, USA). Each supernatant collected was assessed in triplicate. Bovine serum albumin was used as a standard to construct the calibration curve.

2.8. Microscopic examination of PEF-produced chickpea gels

Chickpea gel sample (5 mg, from Section 2.3) was placed on a glass slide and mixed with 10 μL of Lugol staining solution to visualise the swelling and gelatinisation of starch granules (Nilsson et al., 2023). A light microscope (Magnum Ceti, Medline Scientific, Oxford, UK) equipped with a digital camera (XCAM 5.0 MP, ToupTek, Hangzhou, China) at 100 × magnification was used.

2.9. Characterisation of starch and protein structures for PEF-produced chickpea gels using Fourier transform infrared (FTIR) spectroscopy

An ATR-FTIR spectrometer (Cary 630, Agilent, Santa Clara, California, USA) was used to analyse freeze-dried samples (prepared as described in Section 2.5), averaging 60 scans per sample in the range of 4000 to 650 cm^{-1} with a resolution of 2 cm^{-1}. Background spectra were recorded before each sample, and the crystal was cleaned with ethanol prior to each use. Three measurements were performed for each sample. All spectra were pretreated using standard normal variate (SNV). Subsequently, the peak ratio 1047/1022 cm^{-1} was calculated to assess the starch short-ordered structure, while the amide I to amide II ratio (1635/1539 cm^{-1}) was used to evaluate protein structure (de la Rosa-Millán et al., 2018; Wang et al., 2016). To further observe structural changes in secondary protein structures, a second-order derivative was performed on the region between 1600 and 1700 cm^{-1} after Savitsky-Golay smoothing was applied (7-point interval, 2nd polynomial order) (Carbonaro et al., 2012). Data analysis and visualisation were conducted using Origin (version 2018, USA) and Spectragryph (version 1.2.16.1, Germany).

2.10. Determination of starch gelatinisation degree in PEF-produced chickpea gels using differential scanning calorimetry (DSC)

Three milligrams of freeze-dried samples (from Section 2.5) and 7 μL of double-distilled water were loaded, in duplicates, into aluminium hermetic pans and equilibrated for 24 h. The samples were then analysed using a DSC (Discovery 200, TA Instruments, New Castle, Delaware, USA) from 20 to 100 °C at a scanning rate of 10 °C/min, with an empty pan as reference. Onset temperature (T_o), peak temperature (T_p) and gelatinisation enthalpy (ΔH) were obtained from the endothermic peak using TRIOS software (TA Instruments, New Castle, Delaware, USA). Gelatinisation degree (GD) was calculated using Eq. (3) (Duque et al., 2020a,b).

$$GD\ [\%] = \left(1 - \frac{\Delta H\ sample}{\Delta H\ control}\right) \cdot 100 \quad \text{Eq. (3)}$$

2.11. In vitro oral-gastrointestinal digestion procedure of PEF-produced chickpea gels

INFOGEST in vitro digestion procedure (Minekus et al., 2014), with modifications from Johnston et al. (2024) was applied. The analysis was performed in triplicate on selected samples (2 kV/cm 500 kJ/kg, 2 kV/cm 410 kJ/kg, 1 kV/cm 500 kJ/kg, 1 kV/cm 410 kJ/kg and untreated, covering the extremes of the tested conditions in the study). Prior to gastric digestion, 30 mL of chickpea gel samples (from Section 2.3) were consistently broken down via back extrusion with a texture analyser (47 mm vessel diameter, 35 mm probe diameter, 2 mm/s compression speed, 90 % compression). This method was chosen to standardise gel structure disruption. Afterwards, each disrupted chickpea gel sample was transferred to a 100 mL digestion vessel (borosilicate glass), where 2.5 mL of saliva juice (12.5 mg/mL α-amylase, 1.2 mM NaCl, 2 mM KCl, 25 mM $NaHCO_3$) was added and the sample mixture was incubated for 2 min at 37 °C with agitation (55 stroke/min). To terminate the oral digestion phase, the mixture pH was adjusted to pH 3 using 1 M HCl. Then, 10 mL of gastric juice (40 mg/mL porcine stomach pepsin, 151 mM NaCl, 28 mM KCl, 1 mM HCl, pH 3) was added and further incubated for 2 h at 37 °C with agitation. Subsequently, the pH was adjusted to pH 7 using 1 M NaOH to terminate the gastric digestion phase. Then, 20 mL of intestinal juice (10 mg/mL porcine pancreas pancreatin, 8.452 mg/mL porcine bile extract, 0.1 M $NaHCO_3$, pH 7) was added to simulate the small intestinal phase that lasted 4 h at 37 °C with agitation.

Aliquots of digesta were collected from each digestion vessel at predefined timepoints along the gastrointestinal digestion to assess the extent of protein and starch being digested in the control and PEF-obtained chickpea gel samples. To determine protein digestibility, 0.25 mL of digesta was added to a 1.7 mL tube prefilled with 0.25 mL 20 % w/v trichloroacetic acid and stored at 4 °C until analysis within 24 h. To determine starch digestibility, 0.25 mL of digesta was diluted in 1.25 mL sodium acetate buffer (100 mM, pH 5) and immediately boiled for

10 min (TE-10A, Techne, Illinois, USA) to ensure complete inactivation of digestive enzymes prior to 4 °C storage until analysis within 24 h.

2.11.1. Determination of digested protein and starch

Protein digestibility was determined by measuring α-amino groups in the digesta using the *o*-phthaldialdehyde assay (Johnston et al., 2024). The tubes containing digesta were centrifuged (13000 × *g*, 5 min), the resulting supernatant was diluted at a 1:10 ratio, and 26.7 μL of the diluted supernatant was mixed with 200 μL of freshly prepared OPA reagent (0.8 mg/mL *o*-phthaldialdehyde dissolved in buffer containing 2 % ethanol, 50 mM sodium tetraborate, 1 % sodium dodecyl sulphate and 0.2 % 2-mercaptoetanol). Absorbance was measured at 310 nm using a plate reader (Synergy 2, BioTek, Winooski, Vermont, USA). L-serine was used as standard to generate the calibration curve (0–500 mg/mL).

Starch digestibility was determined by measuring glucose levels in the digesta using the total starch assay kit (K-TSTA, Megazyme, Wicklow, Ireland). The diluted digesta were centrifuged (11180 × *g*, 5 min) and 1 mL of the resulting supernatant was quantified for glucose. This was achieved following enzymatic reactions with amyloglucosidase (1 h, 0.05 mL/mL) and glucose oxidase/peroxidase (30 min, 50 °C). Absorbance was measured at 510 nm using a plate reader (Synergy 2, BioTek, Winooski, Vermont, USA).

2.11.2. Determination of total protein and starch in undigested gel samples

To express the results of Section 2.11.1 as a percentage of the total protein or starch present in the chickpea gels, the total α-amino groups and total starch content on undigested sample were determined. Total α-amino groups were quantified by complete digestion of 10 mg of undigested freeze-dried chickpea gel samples in 1 mL of 6 M HCl for 24 h at 110 °C. Subsequently, the acid was evaporated under vacuum (0.08 mbar, 120 min) and the sample was resuspended in 5 mL distilled water prior to *o*-phthaldialdehyde assay. Total starch quantification in undigested samples was determined using Megazyme K-TSTA assay kit (Megazyme, Wicklow, Ireland).

2.11.3. Kinetic modelling of protein and starch digestibility

Experimental data for protein released during gastric and intestinal digestion phases were fitted to a zero order (Eq. (4)) and first order fractional conversion (Eq. (5)) kinetic model, respectively, following the works of (Johnston et al., 2024; Pälchen et al., 2022).

$$y_t = y_o + k_g \cdot t \quad \text{Eq. (4)}$$

$$y_t = y_{max} + (y_o - y_{max}) \cdot e^{-k_i t} \quad \text{Eq. (5)}$$

where t is time (min), k_g and k_i represent the rate constants (min^{-1}) for zero and first order kinetics, respectively (thus referring to gastric and intestinal digestions), while y_t, y_{max} and y_0 corresponded to the % of protein digested at time zero, final (end of intestinal) and time t (0–240 min), respectively.

Data fitting was performed on Matlab (R2024b, USA) using the function "lsqcurvefit", while R^2 adjusted and plotted residuals were utilised to monitor the quality of the fitting. Starch intestinal digestion was characterised by determining the percentages of rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS) based on the work of Alpos et al. (2021).

2.12. Statistical analysis

All analyses were performed at least in triplicate. Statistical differences between samples ($\alpha = 0.05$) were evaluated using either parametric or non-parametric analysis of variance, depending on the characteristics of the data collected. The choice of test was based on preliminary dataset assessments using the Levene test for homogeneity of variance and the Shapiro-Wilk test for normality ($p < 0.05$). If the assumptions of homogeneity and normality were met, a parametric one-way ANOVA followed by Tukey's post-hoc test was conducted. Otherwise, a non-parametric Kruskal-Wallis with Holm's post-hoc test was applied. All statistical analyses were carried out using R (R Foundation for Statistical Computing, Vienna, Austria).

3. Results

3.1. Textural characteristics and IDDSI classification of PEF-produced chickpea gels

Compression tests were performed on each chickpea gel sample to provide quantitative data supporting the IDDSI classification results. Fig. 1b and c show the Young's modulus and the maximum hardness recorded during the compression test for each gel sample, respectively. A clear trend was observed for both texture parameters, where increasing specific energy from 410 to 500 kJ/kg resulted in an exponential increase in both maximum gel hardness (from 0.35 ± 0.01 to 2.94 ± 0.19 kPa) and Young's modulus (from 3.50 ± 0.18 to 109.71 ± 5.90 Pa) of the chickpea gels.

Although the IDDSI classification is based on an empirical assessment, it was adopted in this study as a rapid screening tool to identify the PEF processing parameters that could induce gelation with varying consistencies. The results of fork-drip (Fig. 1a), spoon-tilt (Fig. S1) and fork-press (Fig. S2) tests on chickpea samples prepared after PEF treatment and overnight gel setting (4 °C) collectively highlighted an energy-dependent effect of PEF treatment on chickpea slurry gelation. Starting from an untreated chickpea flour-water slurry showing flour setting and sedimentation, those samples PEF-treated at 410 kJ/kg were classified as "mildly thick fluids" (IDDSI level 2), characterised as fluids that flow from a spoon. PEF treatment at 425 kJ/kg produced chickpea samples classified as "liquidised – extremely thick" (IDDSI level 3), which are considered drinkable but require more time for oral control and tongue propulsion during consumption. PEF treatment at 450–465 kJ/kg induced the formation of gels strong enough to stand on the spoon for the spoon-tilt test, but weak enough to form mounds on a fork with minimal slipping. These gels were considered "pureed – extremely thick" (IDDSI level 4). On the other hand, PEF treatments of 485 and 500 kJ/kg produced stronger chickpea gels classified as "minced and moist" (IDDSI level 5), capable of retaining indentation after the fork-press test but easily smashed before causing blanching of the thumbnail.

Nevertheless, it is important to note that chickpea gels classified within the same IDDSI level do not necessarily exhibit identical textural properties. For example, the maximum hardness of chickpea samples PEF-treated at 500 kJ/kg was nearly double that of samples PEF-treated at 485 kJ/kg (2.94 ± 0.19 and 1.77 ± 0.51 kPa, respectively), despite both behaving very similarly and both being classified as "minced and moist" (IDDSI level 5) (Fig. 1a, S1 and S2).

3.2. Rheological characteristics of PEF-produced chickpea gels

To achieve a more precise characterisation of the PEF-produced chickpea gels, rheological analyses were performed to provide better insights into their soft solid behaviour and fundamental structural properties.

3.2.1. Flow behaviour

All samples clearly demonstrated a shear-thinning flow behaviour, a common characteristic of most food matrices, particularly starch-protein-based gels, where viscosity decreased with increasing shear rate (Fig. 2). It was also found that increasing the specific energy during PEF treatment of chickpea slurries predominantly raised the viscosity of the resulting samples (Fig. 2a, linear fashion $y = 0.06x - 25.7$, $R^2 = 0.75$, x = treatment energy, y = viscosity at 50 s^{-1}) without significantly altering the slope of the flow curve, thereby maintaining a similar shear-thinning behaviour. Typically, a shear stress of 50 s^{-1} is recommended

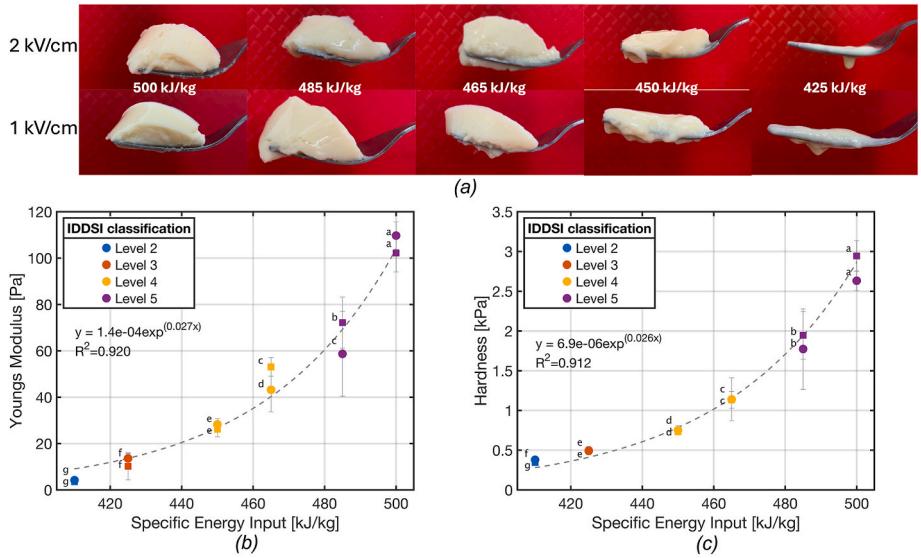

Fig. 1. **(a)** Fork-drip test performed according to the IDDSI framework specifications for selected PEF-fabricated chickpea gel samples. Mean ± standard deviation (n = 5) reported for Young's modulus **(b)** and hardness **(c)** of PEF-fabricated chickpea gel samples. The equations represent the result of exponential fitting where x = specific energy and y = Young's modulus or hardness, respectively. Circles and squares represent chickpea gel samples fabricated using PEF at electric field strengths of 1 and 2 kV/cm, respectively. Each PEF-produced chickpea gel sample was scored according to the IDDSI framework which is illustrated using different symbol colours. Different letters indicate statistically significant differences ($p < 0.05$). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

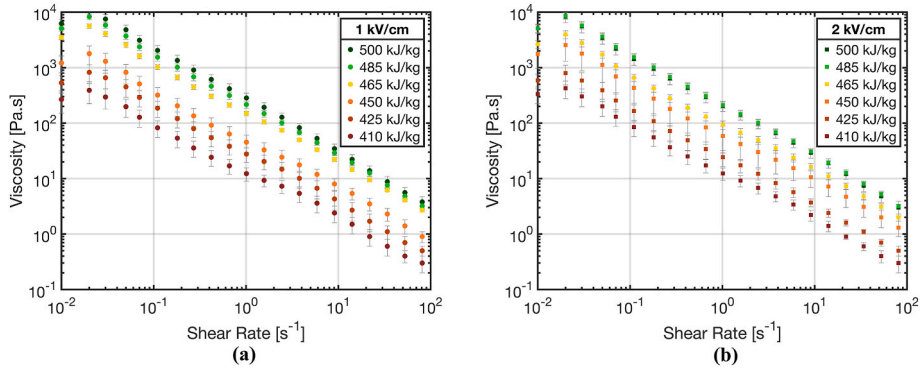

Fig. 2. Viscosity profiles for chickpea gel samples fabricated using PEF at electric field strengths of **(a)** 1 and **(b)** 2 kV/cm, respectively. Points represent the mean ± standard deviation of three independent samples.

by the National Dysphagia Diet (NDD) task force as representative of the stress experienced by the food bolus in the oral cavity to classify food products for dysphagia diets (National Dysphagia Diet Task Force & American Dietetic Association, 2002). The NDD classifications defined viscosity ranges as "thin" (<50 mPa s), "nectar-thick" (51–350 mPa s), "honey-thick" (351–1750 mPa s) and "spoon-thick" (>1751 mPa s). Therefore, those chickpea gel samples obtained by PEF at either 410, 425 or 450 kJ/kg were classified as "honey-thick", despite being classified earlier into three different IDDSI levels (2, 3 and 4, respectively). These discrepancies between the two classifications have also been highlighted by other authors (An et al., 2023; Su et al., 2018) and are likely due to differences in classification criteria: NDD focuses on objective (but limited) measurements, like viscosity at a specific shear rate, while IDDSI adopts a more comprehensive, but empirical, approach and includes additional categories (eight classification levels in IDDSI vs. four classification levels in NDD). Furthermore, relying solely on viscosity at a particular shear rate for product classification comes with limitations, since the stresses experienced by the bolus during swallowing can vary significantly, reaching up to 1000 s^{-1} (Gallegos et al., 2023). Moreover, elongational deformation occurs during swallowing, making it more complex and difficult to characterise with a single rheological parameter (Methacanon et al., 2021; Ong et al., 2018).

3.2.2. *Amplitude sweep*

An amplitude sweep test is generally conducted to identify the linear viscoelastic region (LVR), where loss and storage moduli are independent of amplitude, thus providing important information about the yield stress, which is the critical stress value at which the studied sample begins to flow (Dinkgreve et al., 2016; Mezger, 2020). Moreover, since swallowing involves stresses exceeding the LVR, having an understanding of the food sample behaviour under these conditions becomes crucial (Ren et al., 2024). Oscillatory rheological tests, namely frequency and amplitude sweeps, were not performed on the control sample because its consistency was too liquid to yield meaningful results. In the context of the chickpea gel samples obtained by PEF, both their G'_{LVR} and G''_{LVR} values increased with higher applied specific energy, while tan δ consistently remained below 1 (Fig. 3a and b, Table 2), indicating a strong elastic behaviour, in agreement with the texture analysis results. Additionally, the yield stress (σ_y) of chickpea gels increased as energy applied during PEF treatment increased (Fig. S3b, linear fashion $y = 4.84x - 1999$, $R^2 = 0.90$, x = treatment energy, $y = \sigma_y$). As a result, the application of PEF at a higher energy

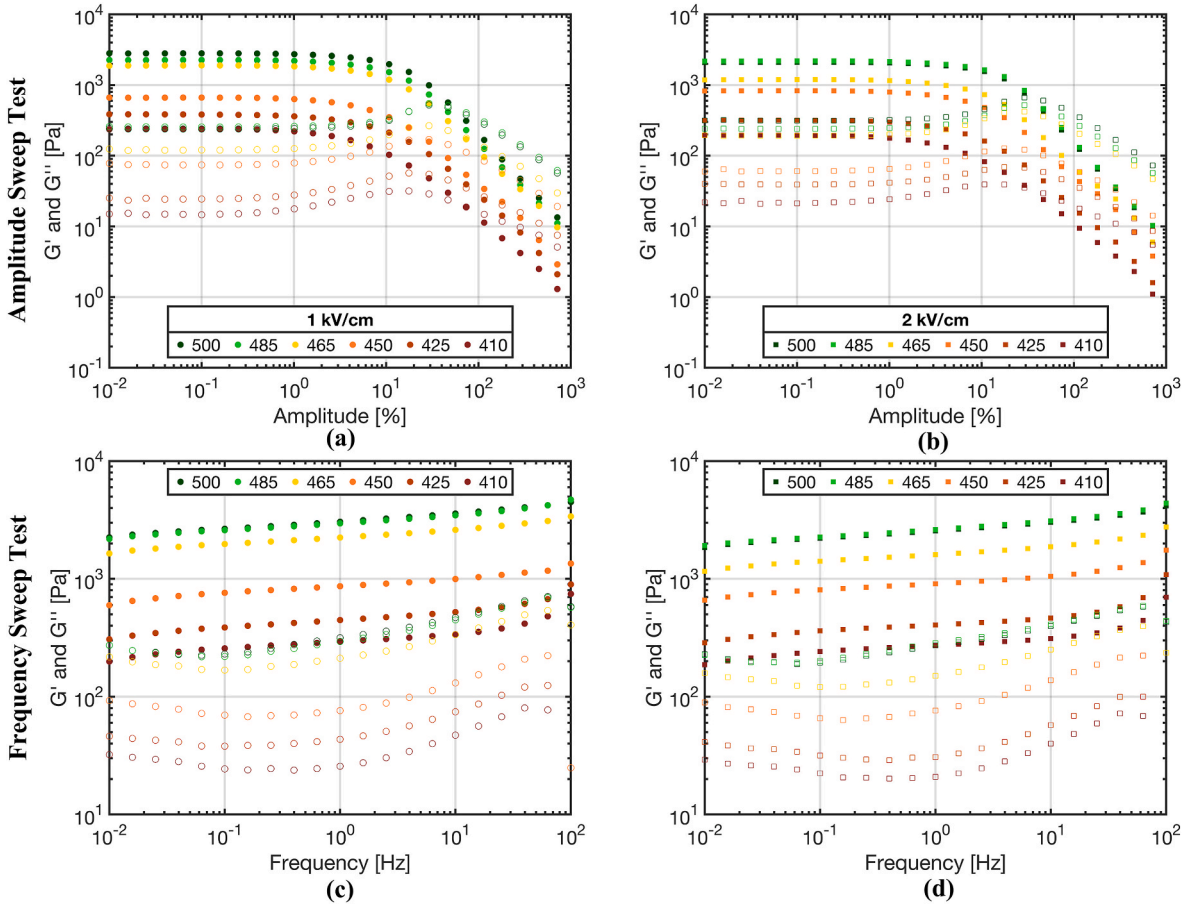

Fig. 3. Amplitude and frequency sweep tests for chickpea gel samples fabricated using PEF at electric field strengths of 1 (**a** and **c**, respectively) and 2 (**b** and **d**, respectively) kV/cm, respectively. Full and empty symbols represent storage and loss moduli, respectively. Points represent the mean of three independent samples.

Table 2
Rheological parameters obtained during amplitude sweep test of PEF-produced chickpea gel samples (mean ± standard deviation, $n = 3$).

Sample code	Elastic modulus G'_{LVR} [Pa] [a]	Loss modulus G''_{LVR} [Pa] [a]	Tan δ_{LVR} [a]	Yield stress σ_y [Pa]
1_500	2811 ± 325^{a}	313 ± 41^{a}	0.111 ± 0.002^{ab}	482 ± 5^{a}
1_485	2264 ± 321^{ab}	239 ± 37^{ab}	0.105 ± 0.002^{bc}	310 ± 48^{bc}
1_465	1899 ± 196^{bc}	191 ± 23^{bc}	0.101 ± 0.002^{c}	269 ± 14^{cd}
1_450	665 ± 220^{de}	61 ± 20^{def}	0.091 ± 0.001^{d}	112 ± 7^{fg}
1_425	383 ± 140^{ef}	39 ± 15^{efg}	0.101 ± 0.003^{c}	55 ± 25^{gh}
1_410	240 ± 52^{fg}	83 ± 106^{def}	0.089 ± 0.001^{d}	15 ± 12^{i}
2_500	2350 ± 466^{ab}	238 ± 65^{ab}	0.113 ± 0.002^{a}	423 ± 135^{ab}
2_485	2418 ± 13^{b}	254 ± 48^{ab}	0.116 ± 0.002^{a}	377 ± 108^{abc}
2_465	1385 ± 14^{cd}	120 ± 35^{cd}	0.100 ± 0.003^{c}	227 ± 7^{de}
2_450	706 ± 286^{d}	61 ± 28^{de}	0.088 ± 0.001^{d}	152 ± 16^{ef}
2_425	318 ± 124^{efg}	24 ± 10^{fg}	0.076 ± 0.001^{e}	34 ± 21^{hi}
2_410	195 ± 42^{g}	15 ± 3^{g}	0.075 ± 0.002^{e}	16 ± 6^{i}

Different letters within the same column indicate statistically significant differences ($p < 0.05$).

[a] G'_{LVR}, G''_{LVR} and tan δ_{LVR} are the average values obtained at amplitudes between 0.01 % and 0.1 %, representing the linear viscoelastic region (LVR).

produced chickpea gels with enhanced stress resistance before flowing, potentially making them suitable for dysphagia patients who require soft, cohesive and non-chewable foods due to progressive tongue weakness.

3.2.3. *Frequency sweep test*

Once LVR is identified in the amplitude sweep test, the subsequent frequency sweep test can gather insights into the internal structure and long-term stability of the food sample. As expected, G′ curves for all PEF-treated chickpea gels showed relatively flat slopes ($0.06<B'<0.15$) with G′ values approximately ten times higher than those of G'', thus indicating a gel-like elastic behaviour (Fig. 3c and d, Table 3) (Mezger, 2020; Xie et al., 2024). Moreover, gels treated with PEF at higher specific energies led to increased G′ and A′ values (Fig. S3c, linear fashion $y = 30.55x - 12519$, $R^2 = 0.92$, x = treatment energy, y = A′), supporting the results from texture analysis and amplitude sweep tests. In contrast, G'' for all PEF-produced chickpea gels demonstrated greater sensitivity ($0.15<B''<0.19$) towards changes in frequency during the rheological analysis, particularly at frequencies above 0.1–1 Hz, with more pronounced changes observed in chickpea gels obtained after exposure to lower specific energies. The loss factor (tan δ) can be used to classify soft gels as either weak paste-like (tan $\delta > 0.1$) or firm self-standing (tan $\delta < 0.1$) (Shim & Mulvaney, 2001); all PEF-produced chickpea gels in the current study mostly exhibited tan δ values between 0.08 and 0.2, depending on the frequency (data not shown). However, the lowest tan δ values were recorded at 0.1 Hz for chickpea gels obtained after higher-energy PEF treatments (>465 kJ/kg), while those obtained after lower-energy PEF treatments reached their lowest tan δ values at approximately 1 Hz. These findings indicate that the maximum elasticity of the studied chickpea gels occurred at different timescales (1 or 10 s), which may be crucial for evaluating their suitability for consumption by dysphagia patients.

Table 3
Rheological parameters derived from fitting frequency sweep results of PEF-produced chickpea gel samples using the Power Law equations (Eqs 1. and 2) (mean ± standard deviation, $n = 3$).

Sample code	A' [Pa.s]	B' [−]	$R^{2'}$	A''[Pa.s]	B'' [−]	$R^{2''}$
1_500	2975 ± 233^{a}	0.071 ± 0.006^{de}	0.984	284 ± 28^{a}	0.157 ± 0.005^{cd}	0.927
1_485	2632 ± 397^{ab}	0.076 ± 0.005^{cde}	0.960	246 ± 36^{ab}	0.159 ± 0.005^{bcd}	0.901
1_465	1817 ± 31^{cd}	0.071 ± 0.006^{de}	0.973	166 ± 2^{cd}	0.163 ± 0.003^{bcd}	0.856
1_450	923 ± 211^{d}	0.061 ± 0.002^{d}	0.936	85 ± 5de	0.176 ± 0.012^{ab}	0.740
1_425	383 ± 93^{e}	0.095 ± 0.014^{abc}	0.866	39 ± 10^{fg}	0.181 ± 0.006^{a}	0.823
1_410	244 ± 95^{e}	0.125 ± 0.004^{ab}	0.757	25 ± 8^{gh}	0.184 ± 0.004^{a}	0.738
2_500	2531 ± 228^{abc}	0.080 ± 0.003^{bcd}	0.963	249 ± 21^{ab}	0.151 ± 0.006^{d}	0.933
2_485	2309 ± 150^{bc}	0.083 ± 0.010^{abcd}	0.954	227 ± 15^{bc}	0.151 ± 0.002^{d}	0.954
2_465	1588 ± 1^{d}	0.081 ± 0.009^{bcd}	0.931	148 ± 4de	0.169 ± 0.007^{abc}	0.854
2_450	942 ± 86^{d}	0.087 ± 0.008^{abc}	0.862	81 ± 0^{ef}	0.175 ± 0.001^{abc}	0.804
2_425	337 ± 152^{e}	0.146 ± 0.012^{a}	0.687	30 ± 11^{gh}	0.173 ± 0.006^{abc}	0.702
2_410	218 ± 134^{e}	0.154 ± 0.060^{abc}	0.741	21 ± 9^{h}	0.185 ± 0.005^{a}	0.700

Different letters within the same column indicate statistically significant differences ($p < 0.05$). $R^{2'}$ and $R^{2''}$ refer, respectively, to the coefficient of determination for Eqs. (1) and (2).

3.3. Susceptibility of PEF-produced chickpea gels to syneresis and soluble protein leaching

Syneresis, defined as the expulsion of water or liquid from a gel network, often occurs in starch-based gels due to molecular rearrangements such as amylose crystallisation and the subsequent shrinkage of the gel network, a phenomenon commonly referred to as starch retrogradation (Morris, 1990). Understanding such behaviour, along with the amount of protein present in the expelled liquid, from the PEF-produced chickpea gels could be useful in providing insights into their structural stability, interactions between chickpea starch and protein, and potential sensory properties. While the application of different electric field strengths (1 and 2 kV/cm) did not appear to influence syneresis in the chickpea gels, the use of higher specific energies during PEF treatment resulted in chickpea gels with significantly reduced syneresis from 56.8 ± 2.0 % to 29.9 ± 1.2 % for 425 kJ/kg and 500 kJ/kg, respectively ($p < 0.05$, Table 4). Interestingly, the protein content in the expelled liquid progressively decreased with increasing specific energies during PEF treatment from 6.2 ± 0.2 mg/mL for 425 kJ/kg to 5.5 ± 0.3 mg/mL after 500 kJ/kg treatments.

Table 4
Syneresis and soluble protein content leached from PEF-produced chickpea gel samples, measured in the supernatant after centrifugation (4500 × *g*, 10 min) (mean ± standard deviation, $n = 3$).

Sample code	Syneresis [%]	Protein content [mg/mL]
1_500	29.8 ± 4.8^{d}	5.7 ± 0.2^{bcd}
1_485	37.2 ± 2.2^{c}	6.0 ± 0.2^{ab}
1_465	40.9 ± 1.6^{bc}	6.0 ± 0.2^{ab}
1_450	44.7 ± 2.2^{b}	6.2 ± 0.2^{a}
1_425	56.1 ± 0.4^{a}	6.2 ± 0.2^{a}
2_500	29.9 ± 1.2^{d}	5.5 ± 0.3^{d}
2_485	38.8 ± 1.8^{bc}	5.8 ± 0.3^{bc}
2_465	41.9 ± 1.7^{bc}	5.8 ± 0.3^{bc}
2_450	43.3 ± 0.8^{bc}	6.2 ± 0.3^{a}
2_425	56.8 ± 2.0^{a}	6.2 ± 0.3^{a}

Different letters within the same column indicate statistically significant differences ($p < 0.05$).

3.4. Microstructural changes in the starch granules and protein bodies of PEF-treated chickpea slurries

To determine whether the chickpea gels formed following PEF treatments were predominantly driven by starch gelatinisation, light microscopy images (Fig. 4) of chickpea slurries were captured after staining with iodine solution, revealing a purple tone in starch granules that faded with increasing swelling and gelatinisation (Nilsson et al., 2023). For the control (untreated) chickpea slurries, intact starch granules (stained dark purple), protein bodies (yellowish particles) and remnants of damaged cells were observed. For those chickpea slurries PEF-treated with increasing applied energy, the starch granules exhibited progressive swelling, though some ungelatinised starch granules were still present in both 410 and 425 kJ/kg-treated samples. At higher-energy PEF treatments, the number of ungelatinised granules in chickpea slurries decreased, though a few remained, likely due to the rapid PEF treatment (44.4–227.4 ms). With increasing specific energy, swollen starch granules in chickpea slurries formed larger and more resistant clumps (even after rigorous mixing following PEF treatment), likely due to greater amylose leaching, which contributed to a more cohesive gel network matrix trapping the starch granules (Morris, 1990). Furthermore, the microscopic images suggested that higher-energy PEF treatments led to increased aggregation and interaction of protein bodies, with larger aggregates forming at the boundaries of swollen starch granules.

3.5. Comparison of the starch and protein structural features of PEF-produced chickpea gels

To better understand the effect of PEF on the starch and protein more specifically, FTIR analysis were performed. Full range FTIR spectra for all chickpea gel samples are presented in Fig. S4, displaying peak arrangements consistent with those previously reported (Chávez-Murillo et al., 2018; Garcia-Valle et al., 2021) where peaks were assigned as follows: 800-1200 cm^{-1} for backbone vibration of C-C, C-N and C-O bonds typical of polysaccharides, 1500-1600 cm^{-1} for amide II generally assigned to N-H bending in peptide bonds of protein molecules, 1600-1700 cm^{-1} for amide I associated with C=O stretching in peptide bonds, 2800-3000 cm^{-1} for C-H stretching in aliphatic groups typically ascribed to lipids, and 3000-3500 cm^{-1} for O-H group interactions through hydrogen bonding between water molecules or other chickpea flour components (Carbonaro et al., 2008; Garcia-Valle et al., 2021). The main parameters of interest in the current study for chickpea were absorbance ratios 1047/1022 and 1635/1539 referring to starch short-range ordered structure and protein overall structure (amide I/II ratio), respectively (Table 5).

The short-ordered crystalline structure in starch granules was evaluated using the absorbance ratio at 1047 and 1022 cm^{-1}, representing ordered and unordered structures, respectively. In all PEF-treated chickpea samples, a decrease in the 1047/1022 ratio was observed compared to the control (untreated) chickpea sample. For chickpea samples PEF-treated at 2 kV/cm, a progressive decrease in the 1047/1022 ratio was observed as the specific energy increased (i.e. from 0.759 ± 0.007 to 0.699 ± 0.005 for control and 500 kJ/kg, respectively). In contrast, for chickpea samples PEF-treated at 1 kV/cm, the ratio decreased overall compared to the control, but no consistent trend was observed with increasing specific energy, with the 1047/1022 ratio values ranging from 0.71 ± 0.00 (1 kV/cm, 500 kJ/kg) to 0.735 ± 0.08 (1 kV/cm, 450 kJ/kg). Such incomplete loss of ordered structure agrees with light microscopy images (Fig. 4) showing the presence of native and partially swollen starch granules. The decrease in the 1047/1022 ratio aligns with similar findings previously reported in PEF-treated oat slurries (Duque et al., 2020a, Duque et al., 2022).

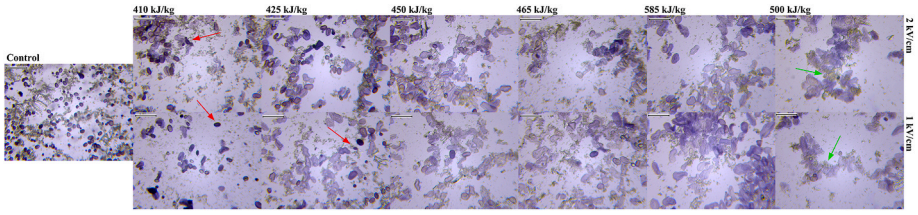

Fig. 4. Light microscopic images (100 × magnification) of untreated and PEF-treated chickpea slurry samples, with starch granules stained purple using iodine Lugol's solution. The white/black scale bar represents 100 μm, while red and green arrows highlight unswollen starch granules and protein body aggregation, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 5
FTIR absorbance ratios for untreated and PEF-treated chickpea samples (mean ± standard deviation, $n = 3$).

Sample code	FTIR absorbance ratios	
	1635/1539 (representing protein overall structure of amide I/II ratio)	1047/1022 (representing starch short-range ordered structure)
Control	1.64 ± 0.02^{de}	0.759 ± 0.007^{a}
1_500	1.95 ± 0.08^{ab}	0.712 ± 0.004^{def}
1_485	2.05 ± 0.07^{a}	0.712 ± 0.013^{de}
1_465	1.80 ± 0.03^{c}	0.735 ± 0.008^{ab}
1_450	1.72 ± 0.04^{cd}	0.735 ± 0.010^{ab}
1_425	1.74 ± 0.05^{cd}	0.730 ± 0.008^{bc}
1_410	1.72 ± 0.03^{cd}	0.719 ± 0.005^{cd}
2_500	2.01 ± 0.05^{ab}	0.699 ± 0.002^{f}
2_485	1.95 ± 0.06^{ab}	0.708 ± 0.009^{ef}
2_465	1.84 ± 0.05^{bc}	0.714 ± 0.005^{de}
2_450	1.71 ± 0.01^{cd}	0.718 ± 0.003^{cd}
2_425	1.77 ± 0.03^{cd}	0.717 ± 0.001^{d}
2_410	1.54 ± 0.05^{e}	0.765 ± 0.016^{a}

Different letters within the same column indicate statistically significant differences ($p < 0.05$).

In the spectral region corresponding to amide I and II, a general trend of increased absorbance ratio at 1635 and 1539 cm^{-1} was observed with increasing specific energy applied to chickpea samples during PEF treatment (Table 5). To gain qualitative insights into the secondary protein structures, second derivative spectra of the amide I region were analysed (Fig. 5). The most affected peaks in all PEF-treated chickpea samples were located at 1640-1635 cm^{-1} (associated with β-sheets) and 1705-1699 cm^{-1} (associated with intermolecular interactions and protein aggregation) (Carbonaro et al., 2008).

3.6. Comparison of the starch gelatinisation degree in PEF-produced chickpea gels

Having observed the central effect of starch in the gel formation, DSC analysis was performed to assess the degree of gelatinisation in the samples. DSC analysis of control (untreated) chickpea samples (Fig. 6) revealed a single broad endothermic peak starting at approximately 60 °C, corresponding to typical gelatinisation phenomena in starch such as granule hydration, molecular rearrangement, crystallite melting and swelling (Ratnayake & Jackson, 2007), as previously observed in chickpea flour (Bashir & Aggarwal, 2016; Kaur & Singh, 2005; Lefèvre et al., 2021). When PEF treatment was applied, all samples exhibited a shift of this endothermic peak to higher temperatures, along with a reduction in peak area, indicating an increased degree of gelatinisation. The effect was particularly pronounced for those chickpea samples PEF-treated at up to 450 kJ/kg, beyond which additional energy had only marginal impacts, since almost full starch gelatinisation was reached (above 450 kJ/kg, gelatinisation degree ranged between 95 and 98 % for all samples).

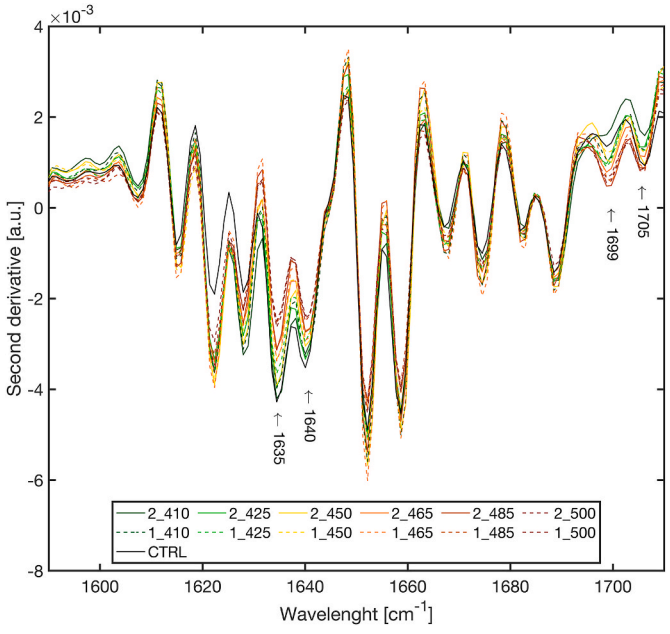

Fig. 5. FTIR spectra (after second derivative application) in the amide I region for untreated and PEF-treated chickpea samples.

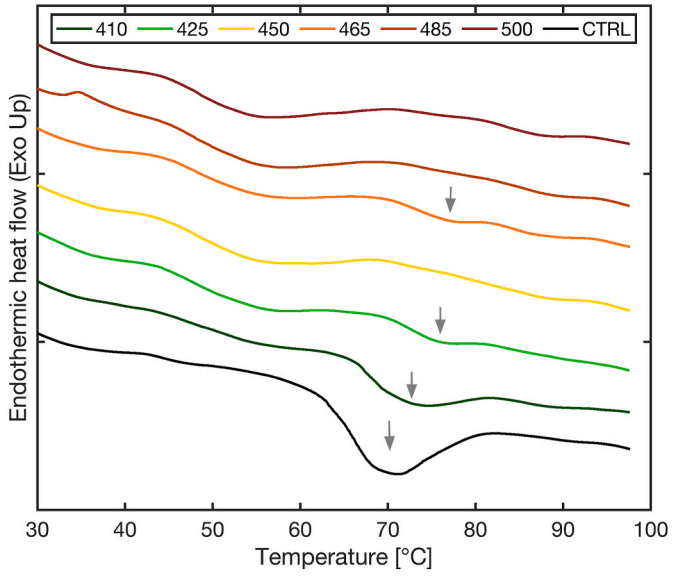

Fig. 6. Examples of single stacked DSC thermograms obtained for untreated and PEF-treated chickpea samples (at 2 kV/cm), highlighting the progressive disappearance and "right-shifting" trend of the gelatinisation peak. Gray arrows indicate the presence of gelatinisation peaks.

3.7. Comparison of the in vitro starch and protein digestibility of PEF-produced chickpea gels

A properly formulated dysphagia product should not only show the desired textural characteristics but also present good nutritional and digestibility properties, thus gastric and intestinal digestion assays were performed on selected samples.

For starch digestion during the in vitro small intestinal phase, all PEF-treated chickpea gel samples exhibited a statistically significant increase in readily digestible starch (RDS%) compared to the control (untreated) sample (Table 6, Fig. S5a). A greater RDS% was observed in gel samples obtained with PEF applied at higher specific energies and higher electric fields. Conversely, resistant starch (RS%) in PEF-treated chickpea gel samples showed an opposing trend, decreasing significantly as specific energy and electric field levels increased.

For protein digestion during the in vitro small intestinal phase, differences between control (untreated) and PEF-treated chickpea gel samples were less pronounced (Fig. S5b), with no statistically significant differences in the estimated final protein hydrolysis %, which averaged at 36 % (y_{max}, Table 6). However, the estimated rate constant of protein digestion demonstrated a statistically significant increase when comparing chickpea gel samples from control and those obtained after exposure to PEF at 2 kV/cm and 500 kJ/kg. These findings suggest that the application of PEF can accelerate protein digestion during the intestinal phase without affecting the final amount of protein digested.

4. Discussion

Chickpea flour, with its high starch (42.94 %) and protein (22.24 %) content, has the potential for gel formation driven by both starch gelatinisation and protein gelation, both mechanisms that could be affected by PEF. During PEF treatment, the rapid application of high voltage pulses induced heating, arising from the Joule effect. This is a sudden and fast heating process (Table 1) that immediately caused the starch gelatinisation and thermal-related changes to chickpea protein. With the help of light microscopy, images of PEF-produced chickpea gels (Fig. 4), showed marked starch granule swelling, suggesting a relatively quick formation of a starch-based network. This network likely formed through hydrogen bond interactions, resulting in a continuous amylose phase. Once starches started to swell and gelatinise, a gel was formed, thus it is possible to infer that the obtained starch-protein composite gel samples were capable of entrapping unswollen starch granules and other flour components (e.g. protein bodies) (Joshi et al., 2014; Lyu et al., 2022; Nilsson et al., 2023). The predominantly starchy nature of the chickpea gel is supported by the lower gelatinisation temperature of starch compared to the denaturation temperature of proteins (70–75 °C and 80–120 °C, respectively (Kaur & Singh, 2005; Lefèvre et al., 2021)), indicating that starch gelatinisation is the faster mechanism driving gel formation for PEF-derived chickpea gels. During PEF treatment, exposure to a higher energy level appeared to gelatinise more starch granules in the chickpea slurries, creating a more cohesive network, as reflected in the increased G′ and hardness recorded for the resulting gels during rheological and textural analysis (Table 2, Fig. 1b and c). In fact, DSC results further confirmed this trend, showing a sharp increase in the degree of starch gelatinisation (GD) reaching around 66–67 % for 410 kJ/kg and 80–90 % for 425 kJ/kg, while those chickpea gels produced with PEF applied beyond 450 kJ/kg showed GD stabilising to approximately 95–98 %, indicating near-full starch gelatinisation because of high energy PEF treatment (Fig. 6). The starch-dominant nature of the chickpea gel was also observed by a relatively high loss factor (tan δ = G''/G′) and sensitivity to frequency (thus a higher B'', Table 3) for all PEF-obtained gels during the frequency sweep test. This aligns with other findings (Shim & Mulvaney, 2001) on thermal treated whey protein-corn starch gels formulated with different starch/protein ratios, where steeper tan δ increase was associated with gels where starch was the predominant constituent. This is due to the entangled polymer network typical of starch-based gels that shows higher B'' compared to protein-based gels, where the nature of the gel is more cross-linked. Together, these results strongly support the potential of high-energy PEF treatment to promote the formation of a starch-dominant gel network by inducing starch gelatinisation during the process.

Chickpea flour, like other legumes such as soy and pea, is a good source of protein, consisting mainly of globulin (S7 and S11), followed by albumins and glutelin (Grasso et al., 2022). Chickpea proteins are recognised to have comparable functional and gelation properties with those of other legumes, although high variation can be observed due to the extraction method and the cultivar variability (Grasso et al., 2022). Therefore, the role of chickpea proteins in the overall gel structure formation for these PEF-produced chickpea gels cannot be overlooked.

Previous studies have shown that when plant proteins are present in lower concentrations than starch, they tend to disrupt the starch gel network by forming inclusions, resulting in reduced gel strength compared to starch-only gels (Lyu et al., 2022; Nilsson et al., 2023; Ren et al., 2024). A previous study (Sun & Arntfield, 2011) further observed that pea protein gelation is highly sensitive to heating and cooling rates, with faster heating rates leading to higher gelation temperatures. Therefore, optimal gel strength for pea protein required a controlled heating rate (2 °C/min). Considering that the heating rates during PEF treatment in this study were much faster (44.4–227.4 ms), it is plausible that such rapid heating rates might hinder gelation of chickpea proteins, potentially shifting their gelation temperature, thus preventing any protein-based gel formation. Nevertheless, stronger chickpea gels obtained by high-energy PEF treatment (>450 kJ/kg) exhibited reduced syneresis and protein losses in the expelled liquid (Table 4), suggesting some degree of interaction and entanglement between starch and protein, even as the gelatinisation degree of starch plateaued (Fig. 6). This improved water retention could be attributed to enhanced interactions between protein molecules and water, likely mediated by hydrogen bonding. Light microscopy images further support the observation of increased aggregation of protein bodies around swollen starch granules for chickpea gel samples from high-energy PEF treatments (Fig. 4). FTIR results also supported these findings, with changes in second derivative spectra indicating protein denaturation occurred (Table 5). Specifically, there appeared to be a loss of β-sheets, an increase in intermolecular

Table 6
In vitro protein digestion (final protein hydrolysis y_{max}, initial protein hydrolysis y_0, rate constant k_i) and starch digestion (readily digestible starch (RDS), slowly digestible starch (SDS), resistant starch (RS))-related parameters for untreated and selected PEF-produced chickpea gel samples (mean ± standard deviation, $n = 3$).

Sample code	Starch intestinal digestion			Protein intestinal digestion			
	RDS [%]	RDS [%]	RDS [%]	y_{max} [%]	y_0 [%]	k_i [× 10^{-2} min^{-1}]	R^2_{adj}
CTRL	16.28 ± 0.15^{c}	13.99 ± 6.73^{a}	69.73 ± 6.81^{a}	36.15 ± 3.04	13.31 ± 1.80 ^{ab}	1.16 ± 0.20^{b}	0.968
2_500	89.06 ± 1.78^{a}	0.71 ± 4.59^{b}	10.24 ± 2.81^{c}	34.34 ± 1.38	10.91 ± 0.27^{c}	1.65 ± 0.04 ^{a}	0.966
2_410	80.24 ± 4.05^{b}	16.78 ± 4.78^{a}	2.98 ± 0.76^{c}	33.46 ± 0.90	11.53 ± 0.51^{bc}	1.42 ± 0.12^{ab}	0.958
1_500	79.83 ± 0.53^{b}	2.73 ± 4.42a^{b}	17.38 ± 4.96^{b}	39.35 ± 0.22	14.81 ± 0.60 ^{a}	1.51 ± 0.22 ^{ab}	0.959
1_410	82.10 ± 3.14^{b}	0.47 ± 2.64^{b}	17.43 ± 2.66^{b}	38.53 ± 2.58	14.20 ± 0.98 ^{a}	1.29 ± 0.39 ^{ab}	0.953

Different letters within the same column indicate statistically significant differences ($p < 0.05$). R^2_{adj} was determined adjusting R^2 for the number of parameters considered in the model.

aggregates, and a rise in the amide I/II ratio alongside a decrease in absorbance values for both amide peaks in all PEF-produced chickpea gels. These structural changes align with observations in legume protein isolates, concentrates and flours subjected to PEF treatments at electric field strengths ranging from 2 to 5 kV/cm up to 50 kV/cm (Duque et al., 2020b; Liu et al., 2011; Melchior et al., 2020; Perez et al., 2024), where the observed changes were attributed to polarisation effects on charged dipoles present in the protein backbone caused by PEF, leading to structural rearrangements. It is plausible that increasing the energy delivered during PEF treatment facilitated protein structural rearrangements in the chickpea slurries, enabling greater interactions with amylose and amylopectin chains. Consequently, it could be that these interactions, facilitated by high-energy PEF treatment, contributed to the formation of firmer chickpea gels with reduced syneresis.

In the current study, chickpea gels obtained using PEF treatments at increasing energy levels showed significant increases in specific textural (hardness) and rheological parameters (yield stress, A′, G'_{LVR}). However, other characteristics of the chickpea gels remained consistent. During the amplitude sweep test, after reaching the critical strain (defined as the end of the LVR where G′ drops below 90 % of its value within the LVR), all PEF-produced chickpea gel samples similarly exhibited a typical type III behaviour (Fig. 3). This behaviour consists of a decrease in G′ accompanied by a weak but sudden rise in G'' (i.e. a temporary increase in G'' as G′ decreases) (Hyun et al., 2011). Similar phenomena have been documented in comparable starch-protein gel matrices (Gu et al., 2024; Ren et al., 2024) and are believed to result from the temporary reorganisation of particles into aggregates or clusters before ultimately breaking down under higher strain amplitudes (Gu et al., 2024; Hyun et al., 2011). When the loss modulus was normalised (G''/G''_{LVR}, data not shown), the increase in G" was consistent across all PEF-produced chickpea gel samples. This consistency suggests that the structural reorganisation responsible for this type III behaviour was not significantly influenced by PEF treatment, even among chickpea gels exhibiting different rheological properties.

While the effect of specific energy on the rheological and textural properties of the PEF-produced chickpea gels was evident, no statistically significant differences were observed between gel samples after PEF treatment at different electric field strengths (Tables 2 and 3, Fig. 1b and c). It can be postulated that Joule heating, driven by the increase in specific energy input and the corresponding temperature rise during PEF treatment, could be a key mechanism contributing to gel formation in the current study. This is supported by the fact that the recorded temperatures of chickpea slurries post-PEF treatment, ranging from 56.4 ± 2.35 to 69.9 ± 1.34 °C (Table 1), aligned closely with the pasting temperature of the chickpea flour (70–75 °C, (Chung et al., 2008; Kaur & Singh, 2005)), and DSC results further supported this observation (Fig. 6). Nevertheless, in previous studies where pure starches (such as corn, cassava, wheat and rice) were PEF-treated with a variable electric field (8–30 kV/cm), a slight reduction in enthalpy was observed combined with a decreased gelatinisation temperature (Milanezzi & Silva, 2025), in contrast to what was observed in the present study on PEF-produced chickpea gels, where a shift to a higher gelatinisation degree appeared (Fig. 6). This discrepancy may stem from the rapid heating induced by the Joule effect during PEF treatment, leading to significant starch granule swelling and high degree of starch gelatinisation, rather than mere structural rearrangement of starch granules. Similar phenomena have been documented by (Ratnayake & Jackson, 2007), who noted shifts in gelatinisation peak temperature and peak area reduction for different starches (rice, corn and potato) under thermal treatment at increasing temperatures (35–85 °C, 5–20 min). Nevertheless, for the purpose of producing dysphagia-friendly food products, complete starch gelatinisation offers distinct advantages, including improved textural consistency and nutrient digestibility of the final product. The Joule effect, often considered undesirable, played a beneficial role for the intended application, enabling rapid gel formation (within microseconds) that minimised sedimentation of insoluble components (e.g. starch and fibres). This rapid heating mechanism highlights the potential of PEF as a rapid and low energy technique for creating tailored gel textures, which may be suitable for dysphagia diet management pending further studies.

Apart from Joule heating, the application of high electric fields during PEF treatment can induce electrochemical reactions and molecular polarisation, as observed in previous studies (Giteru et al., 2018; Milanezzi & Silva, 2025). These phenomena are particularly relevant for structural modifications in macromolecules, such as starch and protein, especially under high electric field conditions. Studies on low electric field applications (1–5 kV/cm) have demonstrated that structural changes are achievable in both starches (Achayuthakan et al., 2023; Conde et al., 2022; Duque et al., 2020b; Qiu et al., 2021) and proteins (Gulzar et al., 2024; Melchior et al., 2020). In the current study, the FTIR amide I/II ratio of chickpea samples increased significantly after 1 and 2 kV/cm electric field treatment (Table 5). This finding contrasts with the FTIR result of Rodriguez Espinosa (2023), who observed no significant changes in the amide I/II ratio of faba beans subjected to steam pressure toasting (0–120 min, 121 °C). Thus, the amide I/II ratio increase might be attributed to the unique effects of PEF, where electric fields induce molecular polarisation and structural rearrangement, independent of the heating caused by the Joule effect.

In all the chickpea gels studied, starch digestibility behaviours during the simulated small intestinal phase appeared to be affected by the intensity of electric field strength applied during PEF treatment (Table 6). Previous studies using low electric field strengths (0.1–1.1 kV/cm) and specific energies of 0.3–150 kJ/kg (Abduh et al., 2019; Castro et al., 2024; Johnston et al., 2024) reported limited improvements in starch digestibility, except in cases where electroporation enhanced starch accessibility to digestive enzymes. At higher electric field strengths (1.25–8.6 kV/cm) and specific energies of 50–500 kJ/kg (Achayuthakan et al., 2023; Conde et al., 2022; Duque et al., 2022; Hong et al., 2018, 2020; Li et al., 2019; Wu et al., 2019), a consistent increase in RDS and reduction in RS were observed, likely due to starch granule disruption, loss of short-ordered structure and partial gelatinisation induced by PEF treatment. Application of PEF treatment beyond 10 kV/cm has been shown to further increase RDS while reducing SDS and RS (Zeng et al., 2016), attributed to more extensive starch granule disruption improving enzyme accessibility. Therefore, despite resulting in similar post-PEF temperature rises and IDDSI classification levels, the observed differences in RDS for chickpea gels obtained by PEF treatments at different electric field strengths suggest that electric field effects contributed to enhancing the digestive enzyme accessibility to starch granules. The instantaneous Joule effect arising from PEF treatment when increasing specific energy could have induced rapid starch gelatinisation, thereby leading to an improved starch digestibility of the resulting chickpea gels. These findings highlight the dual mechanisms of Joule heating and PEF-induced structural modifications on starch, which worked synergistically to improve starch digestibility of the PEF-produced chickpea gels. The ability of PEF technology to enhance starch digestibility of chickpea gels while maintaining their designated IDDSI classification level is particularly valuable for dysphagic patients, who are at higher risk of malnutrition (Foley et al., 2009).

Protein digestibility of chickpea gels during the small intestinal phase (k_i, Table 6) also showed significant differences between control samples and those subjected to PEF treatment, particularly for gel samples obtained with PEF applied at 2 kV/cm and 500 kJ/kg. Previous studies on PEF and plant protein digestion suggest that structural modifications, such as those resulting from electroporation, enhance accessibility of chickpea proteins to digestive enzymes (Alpos et al., 2021; Johnston et al., 2024). For animal proteins, Liu et al. (2018) have reported similar beneficial effects on protein digestibility, attributing the improvement to partial denaturation/unfolding of proteins induced by PEF treatments at high specific energies. These changes are thought to increase surface accessibility of proteins for digestive enzymes. Further research is needed to understand the specific mechanisms

through which PEF-induced electrochemical modifications impact plant proteins to optimise PEF treatments for enhanced protein digestibility, particularly when targeting populations with higher nutritional needs, such as OD-affected patients.

Although the PEF-produced chickpea gels are promising for OD-affected individuals from a textural and rheological perspective, further formulation optimisation by incorporating additional ingredients could improve their stability, consistency, safety, and swallowing effectiveness. One potential strategy is to enhance water retention capacity of the gel to reduce phase separation and eliminate syneresis, while ensuring uniform texture and easier handling during storage and shelf-life. This is particularly critical for OD-affected patients, as inconsistent textures may hinder proper swallowing and increase the risk of aspiration. Another strategy is to increase the energy density (calorie content) of the gel without compromising its gel consistency, making it more nutritionally valuable for OD-affected patients, who are at higher risk of malnutrition. Adding hydrocolloids or optimising PEF parameters could be explored as potential strategies to achieve this goal.

Given that the PEF-produced chickpea gels were predominantly starch-based, further research should explore their textural changes during the oral phase of swallowing, particularly in the presence of salivary amylase, which may hydrolyse starch and compromise gel integrity (Ortega et al., 2020). In the current study, a noticeable decrease in gel viscosity was observed during in vitro gastrointestinal digestion, occurring after the addition of amylase. However, the oral phase in this study was standardised to 2 min in accordance with the INFOGEST protocol (Minekus et al., 2014), considerably longer than the typical 3–20 s duration observed in OD-affected patients (Moon et al., 2018). Future studies should aim to replicate more realistic oral phase conditions to better understand the impact of starch depolymerisation on gel breakdown and the resulting rheological modifications. This will be crucial to determine the actual applicability and safety of the obtained gels for the nutrition of OD-patients as changes in their rheological properties during consumption can have important repercussions on the applicability of the gels. Moreover, the effects of water loss and lubrication during mastication and swallowing process (Matsuo & Fujishima, 2020) deserve further exploration.

5. Conclusion

Overall, the use of PEF technology for gel formation can plausibly be attributed to a combination of mechanisms: primary thermal effects induced by Joule heating, which led to starch gelatinisation, and structural modifications caused by PEF on starch and proteins. Joule heating, on one hand, facilitated rapid temperature increases that caused granule swelling and amylose leaching, forming the gel network (as suggested by the clear specific energy effect (e.g. higher energies increased starch gelatinisation and reduced the 1047/1022 ratio, thus improving the overall textural and rheological properties of the gel). On the other hand, electrochemical effects, such as molecular polarisation, likely contributed to enhanced macromolecular interactions and structural rearrangements between starch, protein and other macromolecules in the chickpea flour. However, the precise role of electrochemical effects, including protein denaturation and starch chain rearrangements, on the functional properties of the gels remains to be fully elucidated, particularly given that digestibility differences observed in chickpea gels between PEF treatments applied at different electric fields were not reflected in the rheological or textural properties of the gels. Therefore, further studies should be conducted to distinguish between effects caused by thermal heating and those induced by electrochemical reaction. This study provides scientific evidence that PEF technology can be used as a sole processing step to tailor textural properties of chickpea flour-water mixtures. By selecting the optimal combination of electric field strength and specific energy, a clean label product can be obtained using a single ingredient, e.g. chickpea flour, with varying rheological properties, that could make it useable for patients with dysphagia. Nevertheless, a more in-depth study such as using videofluoroscopic swallow technique (also possibly considering the effect of endogenous enzymes present in saliva), is necessary to assess the actual sample behaviour during swallowing, ensuring the proper applicability of the product for OD-affected patients.

CRediT authorship contribution statement

Federico Drudi: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Indrawati Oey:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Sze Ying Leong:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Jessie King:** Writing – review & editing, Writing – original draft. **Kevin Sutton:** Writing – review & editing, Funding acquisition. **Urszula Tylewicz:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodhyd.2025.111575.

Data availability

Data will be made available on request.

References

Abduh, S. B. M., Leong, S. Y., Agyei, D., & Oey, I. (2019). Understanding the properties of starch in potatoes (*Solanum tuberosum* var. Agria) after being treated with pulsed electric field processing. *Foods, 8*(5), Article 5. https://doi.org/10.3390/foods8050159

Achayuthakan, P., Wongsagonsup, R., Sriprablom, J., Suphantharika, M., & Intra, P. (2023). Effect of pulsed electric field treatment on the protein, digestibility, and physicochemical properties of starch granules in wheat flour. *Polymers, 15*(20), Article 20. https://doi.org/10.3390/polym15204087

Alpos, M., Leong, S. Y., Liesaputra, V., Martin, C. E., & Oey, I. (2021). Understanding in vivo mastication behaviour and in vitro starch and protein digestibility of pulsed electric field-treated black beans after cooking. *Foods, 10*(11), Article 11. https://doi.org/10.3390/foods10112540

Altman, K. W., Yu, G.-P., & Schaefer, S. D. (2010). Consequence of dysphagia in the hospitalized patient: Impact on prognosis and hospital resources. *Archives of Otolaryngology - Head and Neck Surgery, 136*(8), 784–789. https://doi.org/10.1001/archoto.2010.129

An, S., Lee, W., & Yoo, B. (2023). Comparison of national dysphagia diet and international dysphasia diet standardization initiative levels for thickened drinks prepared with a commercial xanthan gum-based thickener used for patients with dysphagia. *Preventive Nutrition and Food Science, 28*(1), 83–88. https://doi.org/10.3746/pnf.2023.28.1.83

Bashir, K., & Aggarwal, M. (2016). Effects of gamma irradiation on the physicochemical, thermal and functional properties of chickpea flour. *LWT - Food Science and Technology, 69*, 614–622. https://doi.org/10.1016/j.lwt.2016.02.022

Bhuiyan, M. H. R., Liu, L., Samaranayaka, A., & Ngadi, M. (2024). Prediction of pea composites physicochemical traits and techno-functionalities using FTIR spectroscopy. *LWT, 208*, Article 116667. https://doi.org/10.1016/j.lwt.2024.116667

Bhuiyan, M. H. R., Yeasmen, N., & Ngadi, M. (2025). Effect of food hydrocolloids on 3D meat-analog printing and deep-fat-frying. *Food Hydrocolloids, 159*, Article 110716. https://doi.org/10.1016/j.foodhyd.2024.110716

Bradford, M. M. (1976). A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Analytical Biochemistry, 72*(1), 248–254. https://doi.org/10.1016/0003-2697(76)90527-3

Carbonaro, M., Maselli, P., Dore, P., & Nucara, A. (2008). Application of Fourier transform infrared spectroscopy to legume seed flour analysis. *Food Chemistry, 108*(1), 361–368. https://doi.org/10.1016/j.foodchem.2007.10.045

Carbonaro, M., Maselli, P., & Nucara, A. (2012). Relationship between digestibility and secondary structure of raw and thermally treated legume proteins: A fourier transform infrared (FT-IR) spectroscopic study. *Amino Acids, 43*(2), 911–921. https://doi.org/10.1007/s00726-011-1151-4

Castro, L. M. G., Caço, A. I., Pereira, C. F., Sousa, S. C., Alexandre, E. M. C., Saraiva, J. A., & Pintado, M. (2024). Structure and properties of *Quercus robur* acorn starch extracted by pulsed electric field technology. *International Journal of Biological Macromolecules, 260*, Article 129328. https://doi.org/10.1016/j.ijbiomac.2024.129328

Chávez-Murillo, C. E., Veyna-Torres, J. I., Cavazos-Tamez, L. M., de la Rosa-Millán, J., & Serna-Saldívar, S. O. (2018). Physicochemical characteristics, ATR-FTIR molecular interactions and *in vitro* starch and protein digestion of thermally-treated whole pulse flours. *Food Research International, 105*, 371–383. https://doi.org/10.1016/j.foodres.2017.11.029

Chung, H.-J., Liu, Q., Hoover, R., Warkentin, T. D., & Vandenberg, B. (2008). *In vitro* starch digestibility, expected glycemic index, and thermal and pasting properties of flours from pea, lentil and chickpea cultivars. *Food Chemistry, 111*(2), 316–321. https://doi.org/10.1016/j.foodchem.2008.03.062

Cichero, J. A. Y., Lam, P., Steele, C. M., Hanson, B., Chen, J., Dantas, R. O., Duivestein, J., Kayashita, J., Lecko, C., Murray, J., Pillay, M., Riquelme, L., & Stanschus, S. (2017). Development of international terminology and definitions for texture-modified foods and thickened fluids used in dysphagia management: The IDDSI framework. *Dysphagia, 32*(2), 293–314. https://doi.org/10.1007/s00455-016-9758-y

Conde, L. A., Kebede, B., Leong, S. Y., & Oey, I. (2022). Changes in starch in vitro digestibility and properties of cassava flour due to pulsed electric field processing. *Foods, 11*(22), Article 22. https://doi.org/10.3390/foods11223714

Dinkgreve, M., Paredes, J., Denn, M. M., & Bonn, D. (2016). On different ways of measuring "the" yield stress. *Journal of Non-newtonian Fluid Mechanics, 238*, 233–241. https://doi.org/10.1016/j.jnnfm.2016.11.001

Donsì, F., Ferrari, G., & Pataro, G. (2010). Applications of pulsed electric field treatments for the enhancement of mass transfer from vegetable tissue. *Food Engineering Reviews, 2*(2), 109–130. https://doi.org/10.1007/s12393-010-9015-3

Duque, S. M. M., Leong, S. Y., Agyei, D., Singh, J., Larsen, N., & Oey, I. (2020a). Modifications in the physicochemical properties of flour "fractions" after Pulsed Electric Fields treatment of thermally processed oat. *Innovative Food Science & Emerging Technologies, 64*, Article 102406. https://doi.org/10.1016/j.ifset.2020.102406

Duque, S. M. M., Leong, S. Y., Agyei, D., Singh, J., Larsen, N., & Oey, I. (2020b). Understanding the impact of Pulsed Electric Fields treatment on the thermal and pasting properties of raw and thermally processed oat flours. *Food Research International, 129*, Article 108839. https://doi.org/10.1016/j.foodres.2019.108839

Duque, S. M. M., Leong, S. Y., Agyei, D., Singh, J., Larsen, N., Sutton, K., & Oey, I. (2022). Understanding the mechanism of how pulsed electric fields treatment affects the digestibility and characteristics of starch in oat flour. *Applied Sciences, 12*(20), Article 20. https://doi.org/10.3390/app122010293

Foley, N. C., Martin, R. E., Salter, K. L., & Teasell, R. W. (2009). A review of the relationship between dysphagia and malnutrition following stroke. *Journal of Rehabilitation Medicine, 41*(9), Article 9. https://doi.org/10.2340/16501977-0415

Food and Agriculture Organization of the United Nations. (2025). *FAOSTAT statistics database*. Rome: FAO. https://www.fao.org/faostat/en/Licence:CC-BY-4.0. (Accessed 5 February 2025).

Fuente, E. B. la, Staudinger-Prevost, N., Quinchia, L. A., Valencia, C., Partal, P., Franco, J. M., & Gallegos, C. (2012). Design of a new spoon-thick consistency oral nutrition supplement using rheological similarity with a swallow barium test feed. *Applied Rheology, 22*(5). https://doi.org/10.3933/applrheol-22-53365

Gallegos, C., Turcanu, M., Assegehegn, G., & Brito-de la Fuente, E. (2023). Rheological issues on oropharyngeal dysphagia. *Dysphagia, 38*(2), 558–585. https://doi.org/10.1007/s00455-021-10337-w

Garcia-Valle, D. E., Bello-Pérez, L. A., Agama-Acevedo, E., & Alvarez-Ramirez, J. (2021). Effects of mixing, sheeting, and cooking on the starch, protein, and water structures of durum wheat semolina and chickpea flour pasta. *Food Chemistry, 360*, Article 129993. https://doi.org/10.1016/j.foodchem.2021.129993

Giteru, S. G., Oey, I., & Ali, M. A. (2018). Feasibility of using pulsed electric fields to modify biomacromolecules: A review. *Trends in Food Science & Technology, 72*, 91–113. https://doi.org/10.1016/j.tifs.2017.12.009

Grasso, N., Lynch, N. L., Arendt, E. K., & O'Mahony, J. A. (2022). Chickpea protein ingredients: A review of composition, functionality, and applications. *Comprehensive Reviews in Food Science and Food Safety, 21*(1), 435–452. https://doi.org/10.1111/1541-4337.12878

Gu, Y., Xu, R., Liu, T., McClements, D. J., Zhao, X., Wu, J., Zhao, M., & Zhao, Q. (2024). Enhancing the nonlinear rheological property and digestibility of mung bean flour gels using controlled microwave treatments: Effect of starch debranching and protein denaturation. *International Journal of Biological Macromolecules, 270*, Article 132049. https://doi.org/10.1016/j.ijbiomac.2024.132049

Gulzar, S., Martín-Belloso, O., & Soliva-Fortuny, R. (2024). Tailoring the techno-functional properties of fava bean protein isolates: A comparative evaluation of ultrasonication and pulsed electric field treatments. *Foods, 13*(3), Article 3. https://doi.org/10.3390/foods13030376

Hong, J., An, D., Zeng, X.-A., Han, Z., Zheng, X., Cai, M., Bian, K., & Aadil, R. M. (2020). Behaviors of large A-type and small B-type wheat starch granules esterified by conventional and pulsed electric fields assisted methods. *International Journal of Biological Macromolecules, 155*, 516–523. https://doi.org/10.1016/j.ijbiomac.2020.03.184

Hong, J., Zeng, X.-A., Han, Z., & Brennan, C. S. (2018). Effect of pulsed electric fields treatment on the nanostructure of esterified potato starch and their potential glycemic digestibility. *Innovative Food Science & Emerging Technologies, 45*, 438–446. https://doi.org/10.1016/j.ifset.2017.11.009

Hyun, K., Wilhelm, M., Klein, C. O., Cho, K. S., Nam, J. G., Ahn, K. H., Lee, S. J., Ewoldt, R. H., & McKinley, G. H. (2011). A review of nonlinear oscillatory shear tests: Analysis and application of large amplitude oscillatory shear (Laos). *Progress in Polymer Science, 36*(12), 1697–1753. https://doi.org/10.1016/j.progpolymsci.2011.02.002

Johnston, C., Leong, S. Y., Teape, C., Liesaputra, V., & Oey, I. (2024). Low-intensity pulsed electric field processing prior to germination improves in vitro digestibility of faba bean (*Vicia faba* L.) flour and its derived products: A case study on legume-enriched wheat bread. *Food Chemistry, 449*, Article 139321. https://doi.org/10.1016/j.foodchem.2024.139321

Joshi, M., Aldred, P., Panozzo, J. F., Kasapis, S., & Adhikari, B. (2014). Rheological and microstructural characteristics of lentil starch–lentil protein composite pastes and gels. *Food Hydrocolloids, 35*, 226–237. https://doi.org/10.1016/j.foodhyd.2013.05.016

Jukanti, A. K., Gaur, P. M., Gowda, C. L. L., & Chibbar, R. N. (2012). Nutritional quality and health benefits of chickpea (cicer arietinum L.): A review. *British Journal of Nutrition, 108*(S1), S11–S26.

Karki, R., Oey, I., Bremer, P., & Silcock, P. (2022). Pulsed electric fields application in meat processing. In J. Raso, V. Heinz, I. Alvarez, & S. Toepfl (A c. Di (Eds.), *Pulsed electric fields technology for the food industry: Fundamentals and applications* (pp. 399–438). Springer International Publishing. https://doi.org/10.1007/978-3-030-70586-2_14.

Kaur, R., & Prasad, K. (2021). Technological, processing and nutritional aspects of chickpea (Cicer arietinum)—a review. *Trends in Food Science & Technology, 109*, 448–463. https://doi.org/10.1016/j.tifs.2021.01.044

Kaur, M., & Singh, N. (2005). Studies on functional, thermal and pasting properties of flours from different chickpea (Cicer arietinum L.) cultivars. *Food Chemistry, 91*(3), 403–411. https://doi.org/10.1016/j.foodchem.2004.06.015

Khan, A., Carmona, R., & Traube, M. (2014). Dysphagia in the elderly. *Clinics in Geriatric Medicine, 30*(1), 43–53. https://doi.org/10.1016/j.cger.2013.10.009

Lefèvre, C., Bohuon, P., Akissoé, L., Ollier, L., Matignon, B., & Mestres, C. (2021). Modeling the gelatinization-melting transition of the starch-water system in pulses (lentil, bean and chickpea). *Carbohydrate Polymers, 264*, Article 117983. https://doi.org/10.1016/j.carbpol.2021.117983

Li, Q., Wu, Q.-Y., Jiang, W., Qian, J.-Y., Zhang, L., Wu, M., Rao, S.-Q., & Wu, C.-S. (2019). Effect of pulsed electric field on structural properties and digestibility of starches with different crystalline type in solid state. *Carbohydrate Polymers, 207*, 362–370. https://doi.org/10.1016/j.carbpol.2018.12.001

Liu, Z., Chen, X., Li, H., Chitrakar, B., Zeng, Y., Hu, L., & Mo, H. (2024). 3D printing of nutritious dysphagia diet: Status and perspectives. *Trends in Food Science & Technology, 147*, Article 104478. https://doi.org/10.1016/j.tifs.2024.104478

Liu, Y.-F., Oey, I., Bremer, P., Silcock, P., & Carne, A. (2018). Proteolytic pattern, protein breakdown and peptide production of ovomucin-depleted egg white processed with heat or pulsed electric fields at different pH. *Food Research International, 108*, 465–474. https://doi.org/10.1016/j.foodres.2018.03.075

Liu, Y. Y., Zeng, X. A., Deng, Z., Yu, S. J., & Yamasaki, S. (2011). Effect of pulsed electric field on the secondary structure and thermal properties of soy protein isolate. *European Food Research and Technology, 233*(5), 841–850. https://doi.org/10.1007/s00217-011-1580-z

Lyu, Z., Sala, G., & Scholten, E. (2022). Water distribution in maize starch-pea protein gels as determined by a novel confocal laser scanning microscopy image analysis method and its effect on structural and mechanical properties of composite gels. *Food Hydrocolloids, 133*, Article 107942. https://doi.org/10.1016/j.foodhyd.2022.107942

Matsuo, K., & Fujishima, I. (2020). Textural changes by mastication and proper food texture for patients with oropharyngeal dysphagia. *Nutrients, 12*(6), Article 6. https://doi.org/10.3390/nu12061613

Melchior, S., Calligaris, S., Bisson, G., & Manzocco, L. (2020). Understanding the impact of moderate-intensity pulsed electric fields (MIPEF) on structural and functional characteristics of pea, rice and gluten concentrates. *Food and Bioprocess Technology, 13*(12), 2145–2155. https://doi.org/10.1007/s11947-020-02554-2

Methacanon, P., Gamonpilas, C., Kongjaroen, A., & Buathongjan, C. (2021). Food polysaccharides and roles of rheology and tribology in rational design of thickened liquids for oropharyngeal dysphagia: A review. *Comprehensive Reviews in Food Science and Food Safety, 20*(4), 4101–4119. https://doi.org/10.1111/1541-4337.12791

Mezger, T. (2020). *The Rheology Handbook: For users of rotational and oscillatory rheometers*. Vincentz Network. https://doi.org/10.1515/9783748603702

Milanezzi, G. C., & Silva, E. K. (2025). Pulsed electric field-induced starch modification for food industry applications: A review of native to modified starches. *Carbohydrate Polymers, 348*, Article 122793. https://doi.org/10.1016/j.carbpol.2024.122793

Minekus, M., Alminger, M., Alvito, P., Ballance, S., Bohn, T., Bourlieu, C., Carrière, F., Boutrou, R., Corredig, M., Dupont, D., Dufour, C., Egger, L., Golding, M., Karakaya, S., Kirkhus, B., Feunteun, S. L., Lesmes, U., Macierzanka, A., Mackie, A., … Brodkorb, A. (2014). A standardised static in vitro digestion method suitable for food – an international consensus. *Food & Function, 5*(6), 1113–1124. https://doi.org/10.1039/C3FO60702J

Moon, H. I., Yoon, S. Y., Yi, T. I., Jeong, Y. J., & Cho, T. H. (2018). Lesions responsible for delayed oral transit time in post-stroke dysphagia. *Dysphagia, 33*(3), 321–328. https://doi.org/10.1007/s00455-017-9856-5

Morris, V. J. (1990). Starch gelation and retrogradation. *Trends in Food Science & Technology, 1*, 2–6. https://doi.org/10.1016/0924-2244(90)90002-G

National Dysphagia Diet Task Force, & American Dietetic Association. (2002). National dysphagia diet: Standardization for optimal care. *American Dietetic Associati*.

Nilsson, K., Johansson, M., Sandström, C., Eriksson Röhnisch, H., Hedenqvist, M. S., & Langton, M. (2023). Pasting and gelation of faba bean starch-protein mixtures. *Food Hydrocolloids, 138*, Article 108494. https://doi.org/10.1016/j.foodhyd.2023.108494

Ong, J. J.-X., Steele, C. M., & Duizer, L. M. (2018). Sensory characteristics of liquids thickened with commercial thickeners to levels specified in the International Dysphagia Diet Standardization Initiative (IDDSI) framework. *Food Hydrocolloids, 79*, 208–217. https://doi.org/10.1016/j.foodhyd.2017.12.035

Ortega, O., Bolívar-Prados, M., Arreola, V., Nascimento, W. V., Tomsen, N., Gallegos, C., Brito-de La Fuente, E., & Clavé, P. (2020). Therapeutic effect, rheological properties and ?-Amylase resistance of a new mixed starch and xanthan gum thickener on four different phenotypes of patients with oropharyngeal dysphagia. *Nutrients, 12*(6), Article 6. https://doi.org/10.3390/nu12061873

Pälchen, K., Bredie, W. L. P., Duijsens, D., Isaac Alfie Castillo, A., Hendrickx, M., Van Loey, A., Raben, A., & Grauwet, T. (2022). Effect of processing and microstructural properties of chickpea-flours on in vitro digestion and appetite sensations. *Food Research International, 157*, Article 111245. https://doi.org/10.1016/j.foodres.2022.111245

Pematilleke, N., Kaur, M., Adhikari, B., & Torley, P. J. (2024). Meat texture modification for dysphagia management and application of hydrocolloids: A review. *Critical Reviews in Food Science and Nutrition, 64*(6), 1764–1779. https://doi.org/10.1080/10408398.2022.2119202

Perez, J. T., Casanova, F., Queiroz, L. S., Petersen, H. O., García-Moreno, P. J., & Feyissa, A. H. (2024). Protein extraction from yellow mealworm (*Tenebrio molitor*) assisted by pulsed electric fields: Effect on foaming properties. *LWT.* , Article 117041. https://doi.org/10.1016/j.lwt.2024.117041

Qiu, S., Abbaspourrad, A., & Padilla-Zakour, O. I. (2021). Changes in the glutinous rice grain and physicochemical properties of its starch upon moderate treatment with pulsed electric field. *Foods, 10*(2), Article 2. https://doi.org/10.3390/foods10020395

Ratnayake, W. S., & Jackson, D. S. (2007). A new insight into the gelatinization process of native starches. *Carbohydrate Polymers, 67*(4), 511–529. https://doi.org/10.1016/j.carbpol.2006.06.025

Ren, S., Zhang, G., Wang, Z., Sun, F., Cheng, T., Wang, D., Yang, H., Wang, Z., & Guo, Z. (2024). Potentially texture-modified food for dysphagia: Gelling, rheological, and water fixation properties of rice starch–soybean protein composite gels in various ratios. *Food Hydrocolloids, 153*, Article 110025. https://doi.org/10.1016/j.foodhyd.2024.110025

Ribeiro, M., Miquilussi, P. A., Gonçalves, F. M., Taveira, K. V. M., Stechman-Neto, J., Nascimento, W. V., de Araujo, C. M., Schroder, A. G. D., Massi, G., & Santos, R. S. (2024). The prevalence of oropharyngeal dysphagia in adults: A systematic review and meta-analysis. *Dysphagia, 39*(2), 163–176. https://doi.org/10.1007/s00455-023-10608-8

Rodriguez Espinosa, M. E. (2023). *Investigation of the role of amide I to amide II ratio and alpha helix to beta sheet ratio of faba bean seeds in the determination of microbial protein synthesis and animal performance and metabolism in ruminant livestock systems*. Doctoral dissertation. University of Saskatchewan) https://hdl.handle.net/10388/14627.

Shim, J., & Mulvaney, S. J. (2001). Effect of heating temperature, pH, concentration and starch/whey protein ratio on the viscoelastic properties of corn starch/whey protein mixed gels. *Journal of the Science of Food and Agriculture, 81*(8), 706–717. https://doi.org/10.1002/jsfa.869

Su, M., Zheng, G., Chen, Y., Xie, H., Han, W., Yang, Q., Sun, J., Lv, Z., & Chen, J. (2018). Clinical applications of IDDSI framework for texture recommendation for dysphagia patients. *Journal of Texture Studies, 49*(1), 2–10. https://doi.org/10.1111/jtxs.12306

Sun, X. D., & Arntfield, S. D. (2011). Gelation properties of salt-extracted pea protein isolate induced by heat treatment: Effect of heating and cooling rate. *Food Chemistry, 124*(3), 1011–1016. https://doi.org/10.1016/j.foodchem.2010.07.063

Sungsinchai, S., Niamnuy, C., Wattanapan, P., Charoenchaitrakool, M., & Devahastin, S. (2019). Texture modification technologies and their opportunities for the production of dysphagia foods: A review. *Comprehensive Reviews in Food Science and Food Safety, 18*(6), 1898–1912. https://doi.org/10.1111/1541-4337.12495

Taha, A., Casanova, F., Šimonis, P., Stankevič, V., Gomaa, M. A., & Stirkė, A. (2022). Pulsed electric field: Fundamentals and effects on the structural and techno-functional properties of dairy and plant proteins. *Foods, 11*(11), 1556. https://doi.org/10.3390/foods11111556

Wang, S., Zhang, X., Wang, S., & Copeland, L. (2016). Changes of multi-scale structure during mimicked DSC heating reveal the nature of starch gelatinization. *Scientific Reports, 6*(1), Article 28271. https://doi.org/10.1038/srep28271

Wu, C., Wu, Q.-Y., Wu, M., Jiang, W., Qian, J.-Y., Rao, S.-Q., Zhang, L., Li, Q., & Zhang, C. (2019). Effect of pulsed electric field on properties and multi-scale structure of japonica rice starch. *LWT, 116*, Article 108515. https://doi.org/10.1016/j.lwt.2019.108515

Xie, J., Bi, J., Nicolas, J., Christophe, B., Wang, F., & Lyu, J. (2024). Dysphagia food: Impact of soy protein isolate (SPI) addition on textural, physicochemical and microstructural properties of peach complex gels. *Food Hydrocolloids, 154*, Article 110130. https://doi.org/10.1016/j.foodhyd.2024.110130

Zeng, F., Gao, Q., Han, Z., Zeng, X., & Yu, S. (2016). Structural properties and digestibility of pulsed electric field treated waxy rice starch. *Food Chemistry, 194*, 1313–1319. https://doi.org/10.1016/j.foodchem.2015.08.104