# Modelling the mechanical properties and sorption behaviour of pulsed electric fields (PEF) treated carrots and potatoes after air drying for food chain management

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# Biosystems Engineering

# Modelling the mechanical properties and sorption behaviour of pulsed electric fields (PEF) treated carrot and potatoes after air drying for food chain management

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| **Abstract:** | Nowadays, one of the major challenges of the food industry is to turn over to more sustainable processing technologies. To address this change, it is necessary to have more information about available innovative technologies and their effect on different food matrices and processes. The aim of this research was to increase the understanding of the physical modifications induced by the combination of pulsed electric fields (PEF) pre-treatment and further drying in carrot and potato tissues by modelling the sorption isotherms and the textural properties. High coefficient of determination up to 0.980 for GAB and 0.977 for BET were obtained confirming the good ability of both models to describe the sorption isotherm of foodstuff. Either BET and GAB classified carrot in a III type shape and potato in II type shape for sorption isotherm. Mechanical properties for carrot and potato considering all PEF treatment and a w levels were reported and fitted by modified Fermi distribution. High coefficient of determination up to 0.995 confirm the ability of Fermi model to describe mechanical properties in relation to water activity (a w ). |
| **Suggested Reviewers:** | Francisco Barba<br>francisco.barba@uv.es |
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Reviewer #2:

Comment on article YBENG-D-21-00387R1, "Modelling mechanical properties and sorption behaviour of pulsed electric fields (PEF) treated carrot and potatoes after air drying for food chain management".
The article deals with an interesting topic relevant to Biosystems Engineering. Authors made most of the required changes.

Just a minor of couple observations:

Highlight: #1: 50 or 60 °C? (line 122)
Corrected

L102. 9.0 +- 0.1 and 10.0 +- 0.1 mm
Corrected

The captions of Figures are missing.
Checked

Table 1: just correct some significant digits: 0.108 +- 0.032 to 0.11 +- 0.03 and so on.
Corrected

Table 2: the SD for b values are quite strange. Are they 0 after being obtained by fitting from Fermi model?
Corrected

# Highlights

- Potato and carrot treated at 3 PEF intensities and dried at 60ºC.
- High determination coefficient of 0.980 (GAB) and 0.977 (BET) were obtained
- Mechanical properties of all PEF treatments; $a_w$ levels were fitted by Fermi model
- Potato maximum force significantly increases with PEF treatment at 1 and 1.5 kV cm$^{-1}$
- Carrot maximum force showed loss of firmness only for lowest water activity levels

# Modelling the mechanical properties and sorption behaviour of pulsed electric fields (PEF) treated carrots and potatoes after air drying for food chain management

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## Abstract

One of the major challenges of the food industry is to develop more sustainable processing technologies. To address this change, it is necessary to have more information about available innovative technologies and their effect on different food matrices and processes to ensure efficiency in food chain management. The aim of this research was to increase the understanding of the physical modifications induced by the combination of pulsed electric field (PEF) pre-treatment and further drying in carrot and potato tissues by modelling the sorption isotherms and the textural properties. High coefficient of determination up to 0.980 for GAB and 0.977 for BET were obtained confirming the good ability of both models to describe the sorption isotherm of foodstuff. Either BET and GAB classified carrot in a III type shape and potato in II type shape for sorption isotherm. Mechanical properties for carrot and potato considering all PEF treatment and $a_w$ levels were reported and fitted by modified Fermi distribution. High coefficient of determination up to 0.995 confirm the ability of Fermi model to describe mechanical properties in relation to water activity ($a_w$).

**Keywords:** Mechanical properties modelling, Pulsed electric field, Dried vegetables, Sorption Isotherms

## Nomenclature

| | |
|---|---|
| $\hat{y}_i$ | Predicted values (RMSE) |
| $y_i$ | Observed values (RMSE) |
| $a_w$ | Water activity |
| $a_{wc}$ | Characteristic water activity where $Y(a_{wc})=Y/2$ |
| b | Fermi function constant |
| BET | Brunauer, Emmet, and Teller model |
| $C$ | Constant of BET and GAB models |
| GAB | Guggenheim–Anderson–de Boer model |
| $I$ | Current, A |
| $k$ | Constant of GAB model |
| $K$ | Fermi function constant related to the slope of the linear region |
| $m$ | Mass of treated sample, kg |
| $n$ | Number of pulses/observations |
| PEF | Pulsed electric field |
| $R^2$ | Coefficient of determination |
| RMSE | Root mean square error |
| $T_g$ | Glass transition temperature, ºC |
| $U$ | Voltage, V |
| $V_m$ | Monolayer water content (g [water] 100 $g^{-1}$ [solids]) |
| $W_T$ | Energy specific intake, kV $cm^{-1}$ |
| $X$ | Water content, g [water] 100 $g^{-1}$ [solids] |
| $Y(a_w)$ | Mechanical parameter of Fermi function |
| $Y_0$ | Mechanical parameter of Fermi function in the dry state |
| $Y_r$ | Residual mechanical parameter |
| $\Delta w$ | Weight difference |

## 1. Introduction

The food sector as a whole is faced with major challenges that arise from economic and environmental changes, changes in lifestyle, global increases in food consumption, and attitudes of society toward the consequences of food production associated with environmental, social, and economic issues, often captured within the term of sustainability (Fritz & Schiefer, 2008). Thus, the sector needs to innovate in organisational relationships that reach beyond innovations in process improvement by building on the innovation potential inherent in enterprise networks and their flexibility in responding to customers and their demands (Pittaway, Robertson, Munir, Denyer, Neely, 2004). Mathematical modelling is important regarding the scale-shift of the process, from the laboratory to the industrial scale and also allows the phenomena involved in the transformation of food matrices to be parameterised. In food science, transformation processes are integrations of multiple phenomena which result in a complex systems consisting of a large number of interacting microbiological and/or physicochemical components, whose aggregate activities are nonlinear and are responsible for the changes of product properties. Confronted with this complexity, decisions related to the management of such processes increasingly rely on mathematical models that represent the available knowledge about involved phenomena, and that are able to simulate the different transient and equilibrium states over time (Baudrit, Wuillemin, Perrot, 2013).

Considerable research efforts have been carried out on the development of non-thermal processing technologies (Zhang et al., 2010). These technologies permit improving different unit operations in the food industry such as extraction, osmotic dehydration and drying, providing more sustainable and eco-friendly processes (Chemat et al., 2017). One such technology, pulsed electric field (PEF) is a non-thermal technology that has been proposed as pre-treatment. PEF modifies the cell membrane permeability by applying high voltage short time pulses (Barba et al., 2015). The application of low electric field strength creates pores in the biological membrane which affect the mass transfer in tissues (Dellarosa et al., 2016; Dermesonlouoglou, Zachariou, Andreou, Taoukis, 2016; Tylewicz et al., 2017) and it also can promote structural modifications on the final product (E. Iaccheri, Castagnini, Dalla Rosa, Rocculi, 2021; Lebovka, Praporscic, Vorobiev, 2004; Lebovka, Shynkaryk, Vorobiev, 2007).

The physical stability of food products cannot be separated from their sorption isotherm and state diagram. Indeed, water-solid interactions and temperature are among the most important parameters controlling the physical properties of biological systems (Roudaut, 2020). Water and the interactions between water and the other food components control both thermodynamic and dynamic properties (Damodaran, 2017; Eleonora Iaccheri et al., 2019). Also, the effects of water on mechanical properties play an important part in the influence on the mechanical behaviour of a food product, such as crispness or crunchiness (Castagnini, Iaccheri, Tylewicz, Dalla Rosa, Rocculi, 2020). Sears and Darby (1982) stated that water is the most ubiquitous plasticiser in our world. The efficiency of water as a plasticiser is based on the affinity of water molecules for others and its ability to form hydrogen bonds. The plasticising effect of water on solid structures can influence system stability involving in structural changes, such as converting a glass component into a rubber one. This phase transition of the solid state is referred to a range of temperature in which the modification took place recognised as glass transition ($T_g$). Considering a limited humidity range (generally < 11% water), where water keeps its ability to decrease glass transition ($T_g$). Water can also exhibit an anti-plasticising effect with rigidity increasing with increasing water activity ($a_w$) (Castagnini et al., 2020).

PEF treatment can be used as a pre-treatment to enhance drying. Hot air dryers are the most widespread dryers in different industries, not only for food and agriculture applications but also for paper, textile, and chemical ones (Mousakhani-Ganjeh et al., 2021). However, these dryers are characterised by a high energy consumption, low efficiency, and a high impact on the quality of the final product. The reduction of drying time by PEF pre-treatment depends on the applied parameters, drying method, and raw material. Therefore, there is no standard PEF application method, and the effectiveness of electroporation depends on many processing-related parameters. Among parameters, electric field strength and energy input are the most frequently modulated ones and could be used to compare results of different research groups (Barba et al., 2015).

Many studies are reported in the literature on the development of new non-thermal treatments such as PEF, while few deal with the relationship of water sorption properties and structure. The contribution to novelty of this research is devoted to the understanding of the physical modification induced by the combination of PEF pre-treatment and further drying in carrot and potato tissues by modelling the sorption isotherms and textural properties. Carrots and potatoes have been selected since they both contain pectin and starch that are responsible for vegetable texture during thermal processing, but in different proportions. Carrots contain a high pectin and low starch content (Broxterman, Picouet, Schols, 2017) whilst potatoes contain low pectin and starch content (Abduh, Leong, Agyei, Oey, 2019).

The outcome of this study can be used to improve the food chain management in terms of continuous improvement of production process, definition of storage conditions and packaging choices.

## 2. Material and methods

### 2.1. Material and samples preparation

Potatoes (*Solanum tuberosum* var. Agata) and carrots (*Daucus carota* var. Amsterdam) were purchased from the local market in Cesena, Italy and stored at 10°C until processing. Fresh potato, and carrot water content was of 5.7 ± 0.6 and 9.8 ± 0.4 kg [water] kg [dry mass], respectively (AOAC official method n. 934.06). Samples were cut into cylindrical shape (length: 10.0 ± 0.1 mm; diameter: 9.0 ± 0.1 mm) by using a manual cork borer.

### 2.2. Pulsed electric field and air-drying treatments

Twenty pieces of potatoes and carrots per treatment were placed in a 50 × 50 × 50 mm treatment chamber. Each piece had a weight of 1.3 ± 0.2g. Tap water (515 ± 20 μs $cm^{-1}$ conductivity) was used to fill up the treatment chamber in a 1:2 ratio, sample to water. The conductivity was measured using an electrical conductivity meter mod. Basic 30 (Crison Instrument, Spain). A pulse generator mod. S-P7500 60A 8kV (Alintel srl., Bologna, Italy) was applied for PEF treatment. Near-rectangular shaped pulses, with a pulse width of 10 μs and frequency of 100 Hz were applied, as previously reported (Castagnini et al., 2020; E. Iaccheri et al., 2021). 0.5, 1 and 1.5 kV $cm^{-1}$ field strength were tested at 25ºC. Controls non-PEF treated samples (0 kV) were also prepared. The total treatment time was set to 1 s. The calculated energy specific intake ($W_T$) for the samples treated at 0.5, 1 and 1.5 kV $cm^{-1}$ was 0.121, 0.483 and 1.086 kJ $kg^{-1}$ respectively. The $W_T$ for rectangular pulse was calculated as follows:

$$W_T = \frac{n}{m}\int_0^\infty U(t).I(t)dt \qquad (1)$$

Where *n* is the number of pulses applied, m is the mass of treated sample, *U(t)* is the voltage across the treatment chamber and *I(t)* is the current through the treatment chamber (Raso et al., 2016). Immediately after PEF treatment, carrot and potato samples were dried at 2 m $s^{-1}$ in a tray air drier at 60 ºC (mod. CLW 750 TOP+, Pol-Eko- Aparatura SP.J., Poland), with transverse airflow, an air renewal fee of 50% and a sieve load of 54 kg $m^{-2}$ until a water activity ($a_w$) target of 0.2 (about 6 hours). The samples were putted in perforated trays. The $a_w$ was measured with a dewpoint hygrometer (Aqualab, Decagon Devices Inc., Pullman, WA, USA). The treatment was carried out three times.

## 2.3. Sorption isotherm

The traditional saturated salt slurry method was used to reach different thermodynamic equilibrated relative humidity values. Firstly, air dried samples were conditioned by putting them into a desiccator with $P_2O_5$ to reach a complete dehydration, by monitoring three consecutive constant weight ($\Delta w$<0.0005g). Afterwards, carrot and potato samples were positioned in the hermetically closed desiccator (DES 2000) containing the saturated salt solutions which correspond to the required $a_w$ (0.113 LiCl; 0.225 $CH_3CO_2K$; 0.331 $MgCl_2$; 0.432 $K_2CO_3$; 0.576 NaBr and 0.753 NaCl). The thermodynamic equilibrium took place at 22 ± 1°C. Each hydration experiment comprised a reference sample and samples treated at specific field strengths (0.5, 1 and 1.5 kV $cm^{-1}$). Samples were periodically checked until a constant weight for three consecutive measurements were reached ($\Delta w$< 0.0005 g). The equilibrium was also verified by $a_w$ measurement. Water content was gravimetrically determined by using oven drying at 70°C until reaching steady mass, and herein expressed on dry matter basis (AOAC 934.06).

Brunauer, Emmet, and Teller (BET) (Eq.(2)) and Guggenheim–Anderson–de Boer GAB (Eq. (3)) expressions were used to fit each experimental measurement of moisture and water activity:

$$X = \frac{V_m\, C\, a_w}{(1-a_w)(1+(C-1)a_w)} \qquad \text{eq. 2}$$

$$X = \frac{V_m\, C\, k\, a_w}{(1-k\, a_w)(1-k\, a_w+C\, k\, a_w)} \qquad \text{eq. 3}$$

Where $X$ is the water content (g [water] 100 $g^{-1}$ [solids]), $a_w$ is the water activity, $V_m$ is the monolayer water content (g [water] 100 $g^{-1}$ [solids]), $k$ is a constant related multilayer molecules interaction with the sorbent and $C$ is the constant related to monolayer sorption heat (Barbosa-Canovas & Fontana, 2020).

The GAB and BET equations are the most used to describe the behaviour of foodstuffs (Al-Muhtaseb et al., 2002; Barbosa Canovas, 2020; Knani et al., 2012; Wiktor et al., 2013). The BET equation, in particular is considered the most appropriate equation to determine the sorption behaviour in mid-low water activity range, such as dehydrated vegetables. It estimates well monolayer moisture content, which is a crucial parameter for product stability assessment, determining the quantity of water un-available for physical structure modifications (Roos & Karel, 1991).

## 2.4. Mechanical properties

Mechanical properties of equilibrated carrots and potatoes were analysed by a texture analyser mod. TA.XT2 (Stable Microsystems, Godalming, Surrey, UK) equipped with a 25 kg load cell and a craft knife blade of 0.5 mm thick. Test speed was set at 0.25 mm $s^{-1}$, 100% distance, and at least 10 measurements were carried out for each sample. The cutting/shearing test applies compression and shear forces (Nunak & Schleining, 2011). Maximum force at yield point (maximum cutting force, N), was calculated from force-distance curves by means of Exponent Software v.6.1.16.0 (Stable Micro Systems - www.stablemicrosystems.com).)

## 2.5. Modelling of texture properties

Mechanical parameters and $a_w$ can be related to describe different structural behaviour by applying Fermi distribution function (Eq. (4)) (Wollny & Peleg, 1994):

$$Y_{(aw)} = \frac{Y_0}{1+\exp\left(\frac{aw-aw_C}{b}\right)} \tag{4}$$

where $Y$ ($a_w$) is the magnitude of the mechanical parameter, $Y_0$ is its magnitude in the dry state, $a_{wc}$ is a characteristic $a_w$ where $Y$ ($a_{wc}$) = $Y$/2 and $b$ is a constant accounting for the gradients of the relationships around $a_{wc}$.

Particular cases does not properly follow sigmoidal distribution, therefore the modified Peleg-Fermi model (Harris & Peleg, 1996) is more suitable for data interpolation (Eq. (5)):

$$Y_{(aw)} = \frac{Y_0 - Y_r + K a_w^n}{1+\exp\left(\frac{aw-aw_C}{b}\right)} + Y_r \tag{5}$$

where, $K$ is a constant that roughly represents the slope of the linear region and ($Y_r$) a term which accounts for the residual magnitude of $x$ ($a_w$). Each experimental replicate was modelled individually.

### 2.6. Statistical analysis

The BET and GAB equations were applied to moisture content and water activity experimental data (Statistica 7.0 (Statsoft Inc. - www.statistica.com)) and Marquardt algorithm (Mathematics, 1977). The algorithm calculates the root mean  square error (RMSE) values were employed to evaluate model performance (Eq. (6)):

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y_i} - y_i)^2}{n}} \qquad (6)$$

$\hat{y_i}$are predicted values, $y_i$ are observed values and *n* is the number of observations.

Significant differences among means of maximum force at different PEF treatment were analysed by means of ANOVA (analysis of variance, p-level < 0.05, post-hoc Tukey, Statgraphics Centurion XVI software (Statgraphics Technologies, Inc. - www.statgraphics.com). For clarity, no difference among means does not report letters.

## 3. Results and discussion

Sorption isotherms of carrot and potato were carried out to characterise sorption behaviour of these vegetables as a function of PEF treatment. Knowing the effects of water absorbed and adsorbed on tissues treated with different PEF intensity could be helpful to process development and managing of product storage. In addition, water state in a complex matrix involves inhomogeneous distribution of the molecules among structures having important roles in chemico-physical modifications. Sorption isotherms of dried carrot and potato PEF pre-treated samples were fitted with BET and GAB equations (Eqs. (2) & (3)). Experimental data (symbols) and BET fitting (lines) for both carrot and potato are shown in Fig. 1.

Sorption isotherms of carrot and potato have non-linear curves as in general reported for foodstuffs, (Barbosa-Canovas & Fontana, 2020). Carrot and potato samples showed different curves shapes as results of different state of system constituent. According to BET classification, sorption isotherms of carrot were typically of type III, while potato were of type II. The type III is generally related to matrix with crystalline components, such as sugar and salt presence, small molecules available for moisture interactions. The type II of sorption isotherm is sigmoidal, and it is characterized by two regions from 0.2 to 0.4 where physical modification begins, and from 0.6 to 0.7, where chemical effects are mainly presents (Barbosa-Canovas & Fontana, 2020). PEF treatment appears to not affect the shape of sorption isotherms for carrot and potato, as previously reported for apple by Castagnini et al., (2020).

BET and GAB equations showed a good agreement with experimental data concerning high $R^2$ for all different samples, as reported in Table 1.

Table 1. Sorption isotherm parameters for BET and GAB equations and related coefficient of determination ($R^2$) and root mean square error (RMSE) for all PEF treatments.

| **Sample** | **Equation** | **Parameters** | **Control** | **0.5 kV cm$^{-1}$** | **1 kV cm$^{-1}$** | **1.5 kV cm$^{-1}$** |
|---|---|---|---|---|---|---|
| **Carrots** | BET | $V_m$ | 0.11 ± 0.03 | 0.10 ± 0.02 | 0.13 ± 0.05 | 0.14 ± 0.06 |
| | | C | 1.3 ± 0.3 | 1.8 ± 0.3 | 0.988 ± 0.006 | 0.980 ±0.004 |
| | | $R^2$ | 0.964 | 0.977 | 0.975 | 0.964 |
| | | RMSE | 0.010 | 0.008 | 0.008 | 0.008 |
| | GAB | k | 3.1 ± 0.2 | 2.6 ± 0.4 | 0.05 ± 0.01 | 0.39 ± 0.06 |
| | | $V_m$ | 0.09 ± 0.03 | 0.11 ± 0.06 | 2.0 ± 0.3 | 0.43 ± 0.06 |
| | | C | 0.51 ± 0.08 | 0.52 ± 0.03 | 1.29 ± 0.05 | 0.78 ± 0.04 |
| | | $R^2$ | 0.964 | 0.979 | 0.980 | 0.963 |
| | | RMSE | 0.011 | 0.008 | 0.007 | 0.009 |
| **Potatoes** | BET | $V_m$ | 0.04 ± 0.01 | 0.04 ± 0.02 | 0.045 ± 0.009 | 0.04 ± 0.02 |
| | | C | 49.5 ± 0.5 | 42.4 ± 0.7 | 22.3 ± 0.9 | 184.2 ± 0.4 |
| | | $R^2$ | 0.902 | 0.857 | 0.930 | 0.887 |
| | | RMSE | 0.008 | 0.012 | 0.006 | 0.010 |
| | GAB | k | 0.089 ± 0.003 | 0.10 ± 0.02 | 0.10 ± 0.02 | 0.19 ± 0.01 |
| | | $V_m$ | 0.23 ± 0.03 | 0.27 ± 0.07 | 0.20 ± 0.02 | 0.12 ± 0.04 |
| | | C | 12.9 ± 0.3 | 8.4 ± 0.5 | 11.9 ± 0.3 | 11.9 ± 0.5 |
| | | $R^2$ | 0.951 | 0.975 | 0.923 | 0.960 |
| | | RMSE | 0.004 | 0.002 | 0.006 | 0.003 |

BET and GAB equations belong from the same family, although BET can be more suitable for monolayer value estimation. The monolayer value has been found to be crucial for stability description, particularly for dried products. Carrot monolayer value estimated with BET increase as a function of electric field strength. Accordingly, PEF treatment on carrot samples at high electric field strength could led more site for water H-bonding. This behaviour could be also compatible with the type III of sorption isotherm shape, characterised by adsorption phenomena accounting for solid surface interactions (Barbosa-Canovas & Fontana, 2020). This effect could be also considered, as PEF is widely recognised for cell membrane disruption enhancement (Lebovka, Bazhal, Vorobiev, 2002; Lebovka et al., 2007; Liu, Grimi, Lebovka, Vorobiev, 2018). An opposite trend was verified for potato samples; monolayer values does not change because of PEF treatment. Sorption isotherms of potato were characterized by type II shape, more related to absorption mechanisms, as water internalization into solids (Barbosa-Canovas & Fontana, 2020).

The GAB equation is one of the most used equation concerning food modelling and it fits also very well to experimental data. Parameter *C* of the GAB equation is used to define type of sorption isotherms, characterising carrot in the type III, with C value > 2 (Blahovec & Yanniotis, 2008) and potato in the type II, with *C* value 0 > *C* > 2, confirming BET classification.

The *k* parameter is related to the entropic contribution of mobility and configuration of water with molecules of multilayer (Quirijns, van Boxtel, van Loon, van Straten, 2005). When *k* is near to unity, molecules behave like liquid, conversely when *k* is has lower value the molecules are structured in multilayers (Quirijns et al., 2005). In this way, water in potato seems more structured in multilayers than that in carrot, and not so affected by PEF treatment. PEF treatment showed only slight effects on sorption isotherms, but could probably has more effects on solids structure transition, such as glass transition, as previously reported (E. Iaccheri et al., 2021).

Mechanical properties of carrot and potato were carried out for all the $a_w$ levels, as shown in Fig. 2. As expected, maximum force decreases with an increase of hydration level for both carrot and potato. This typical trend is probably a consequence of the plasticisation effect of water, previously reported mainly for matrix rich in carbohydrate structures (Kalichevsky & Blanshard, 1993).

Mechanical parameter of maximum force was modelled by Fermi modified equation (Eq. (5)) to estimate the texture loss as a function of $a_w$ level. The results were reported in Table 2.

Table 2. Parameters for modified Fermi equation calculated on $a_w$ and maximum force (N)

| **Sample** | **Treatment** | $Y_0$ | $X_c$ | $Y_r$ | ***b*** | $R^2$ | **RMSE** |
|---|---|---|---|---|---|---|---|
| **Carrot** | Control | 50 | 0.38 | 7 | 0.084±0.001 | 0.995 | 1.17 |
| | 0.5 **kV cm$^{-1}$** | 42 | 0.50 | 7 | 0.061±0.001 | 0.978 | 2.21 |
| | 1.0 **kV cm$^{-1}$** | 35 | 0.51 | 5 | 0.060±0.002 | 0.956 | 2.54 |
| | 1.5 **kV cm$^{-1}$** | 28 | 0.60 | 7 | 0.064±0.003 | 0.864 | 3.47 |
| **Potato** | Control | 28 | 0.75 | 19 | 0.150±0.004 | 0.876 | 1.32 |
| | 0.5 **kV cm$^{-1}$** | 31 | 0.80 | 17 | 0.161±0.001 | 0.941 | 1.21 |
| | 1.0 **kV cm$^{-1}$** | 46 | 0.85 | 25 | 0.084±0.001 | 0.961 | 1.41 |
| | 1.5 **kV cm$^{-1}$** | 48 | 0.85 | 24 | 0.143±0.002 | 0.909 | 2.62 |

High coefficients of determination, ranging from 0.864 to 0.995 for carrots and from 0.876 to 0.961 for potatoes, confirmed that Fermi distribution was appropriate to describing plasticisation effect of water on textural properties. The parameter $X_c$ is the critical $a_w$ level related to system modification such a transition range, likewise for the glass transition temperature. Higher $X_c$ values for model created by highest electric field strength underlined a mechanical modification related to PEF treatments. Higher critical $a_w$ level of carrots ranging from 0.5 to 0.6 for PEF treated samples compared to the control one, described that treated product were more sensible to phase transition and physical modifications. Potato samples started from high critical $a_w$ level showing only a slight increase.

Accordingly, mechanical properties modifications were also discussed as a function of PEF treatment intensity, as previously reported on another foodstuff (Castagnini et al., 2020).

Maximum force, corresponding to the firmness of carrot and potato was measured for all PEF intensities at all $a_w$ levels investigated. Average values, standard deviations, and significant differences among samples at different PEF treatment (keeping constant $a_w$), are reported in Table 3.

Table 3. Maximum force (N) at different PEF treatments (mean values and standard deviation). Letters indicates difference among treatments means, p-level <0.05. No difference among means does not report letters.

| **Sample** | **$a_w$** | **Control** | **0.5 kV cm$^{-1}$** | **1.0 kV cm$^{-1}$** | **1.5 kV cm$^{-1}$** |
|---|---|---|---|---|---|
| **Carrot** | 0.113 | $50 \pm 9^{a}$ | $42 \pm 8^{ab}$ | $35 \pm 10^{b}$ | $28 \pm 2^{c}$ |
| | 0.225 | $44 \pm 11^{a}$ | $44 \pm 4^{a}$ | $32 \pm 9^{ab}$ | $29 \pm 8^{b}$ |
| | 0.331 | 37 ± 7 | 42 ± 11 | 37 ± 10 | 33 ± 5 |
| | 0.432 | 19 ± 4 | 25 ± 4 | 21 ± 9 | 29 ± 3 |
| | 0.576 | 11 ± 2 | 11 ± 2 | 11 ± 4 | 14 ± 3 |
| | 0.753 | 7 ± 1 | 7 ± 1 | 5 ± 2 | 7 ± 1 |
| **Potato** | 0.113 | $28 \pm 8^{a}$ | $31 \pm 8^{a}$ | $46 \pm 7^{b}$ | $48 \pm 11^{b}$ |
| | 0.225 | $24 \pm 6^{a}$ | $31 \pm 3^{ab}$ | $41 \pm 9^{bc}$ | $46 \pm 11^{c}$ |
| | 0.331 | $21 \pm 7^{a}$ | $26 \pm 6^{a}$ | $39 \pm 8^{b}$ | $48 \pm 4^{b}$ |
| | 0.432 | $19 \pm 5^{a}$ | $24 \pm 6^{a}$ | $40 \pm 11^{b}$ | $36 \pm 9^{b}$ |
| | 0.576 | $18 \pm 6^{a}$ | $22 \pm 4^{ab}$ | $31 \pm 8^{bc}$ | $36 \pm 9^{c}$ |
| | 0.753 | $19 \pm 2^{a}$ | $17 \pm 3^{a}$ | $24 \pm 4^{b}$ | $24 \pm 5^{b}$ |

As previously reported by Lebovka, Praporscic and Vorobiev (2004) firmness, extrapolated by curves as the maximum force, of carrot control samples were higher than that of potato control samples. Lebovka, Praporscic and Vorobiev (2004) concluded that carrot and potato tissue did not change structure after PEF treatment, despite the widely accepted concept of tissue rupture and loss of structure integrity. In particular, PEF treatment did not provoke loss of firmness in samples, such as potato, where starch is one of the major components (Lebovka et al., 2004). In a present study, potato maximum force significantly increased with PEF treatment at 1 and 1.5 kV cm$^{-1}$. Carrot samples showed a loss of firmness for the lowest $a_w$ levels (0.113 and 0.225) and no differences in structures for the other $a_w$ levels accounting for PEF treatments.

## 4. Conclusions

GAB and BET equations were applied to experimental data to understand sorption behaviour as a function of PEF treatment for dried carrot and potato, respectively. High determination coefficient of 0.980 for GAB and 0.977 for BET were obtained confirming the ability of both models to accurately describe the sorption isotherm of foodstuff. BET and GAB modelling permitted to classify carrot and potato isotherms of type III and type II shape, respectively. Carrot monolayer value estimated by the

BET equation increased as a function of PEF treatment intensity, whilst potato did not reveal differences promoted by the different treatments. Mechanical properties for carrot and potato considering all PEF treatments and $a_w$ levels were reported and fitted by modified Fermi distribution. High coefficient of determination up to 0.995 confirmed the ability of Fermi model to describe mechanical properties in relation to sample $a_w$. Particularly, the model highlighted the plasticisation effect of water on carrot and potato mechanical properties. Considering PEF, carrot treated samples were characterized by higher critical $a_w$ level ranging from 0.5 to 0.6 than that of the control with $a_w$ of 0.38. This phenomenon was of less intensity considering potato samples. Particularly the higher critical $a_w$ level indicates more sensibility to physical modifications such as phase transitions.
Furthermore, potato maximum force significantly increased with PEF treatment at 1 and 1.5 kV $cm^{-1}$, while carrot samples showed a loss of firmness only for the lowest water activity levels.
Accordingly, PEF affected carrot and potato mechanical properties, increasing sample sensibility to physical modifications, giving important highlights in the optic of new processing and chain management strategies. The obtained results can be helpful in design and management of a production process in which new non-thermal technologies, such as PEF, will be introduced. Information about product stability can be used to increase understanding in product structures modification, an important step for storage condition setting and packaging choice.

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Figure 1

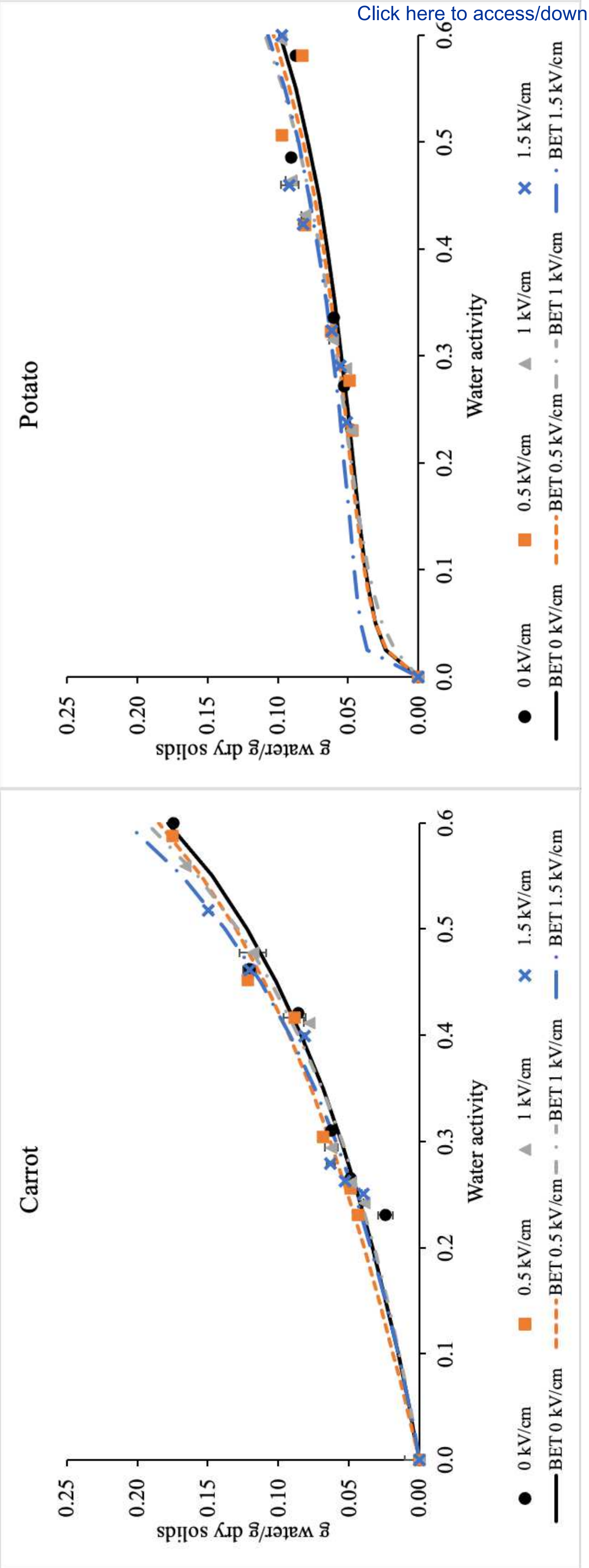
Carrot
Potato
g water/g dry solids
0.00
0.05
0.10
0.15
0.20
0.25
Water activity
0.0
0.1
0.2
0.3
0.4
0.5
0.6
● 0 kV/cm
■ 0.5 kV/cm
▲ 1 kV/cm
× 1.5 kV/cm
BET 0 kV/cm
BET 0.5 kV/cm
BET 1 kV/cm
BET 1.5 kV/cm

Figure 2

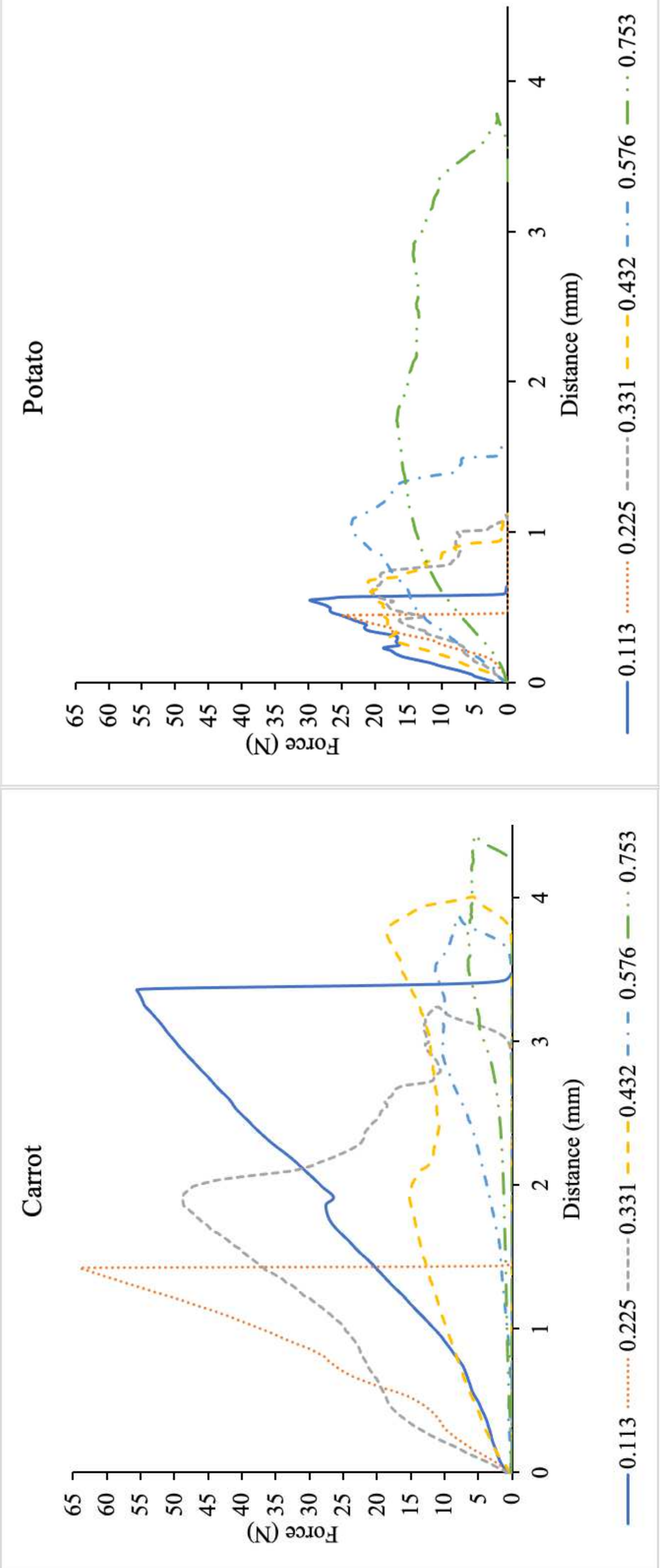
Carrot
Force (N)
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0
1
2
3
4
Distance (mm)
0.113
0.225
0.331
0.432
0.576
0.753
Potato
Force (N)
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0
1
2
3
4
Distance (mm)
0.113
0.225
0.331
0.432
0.576
0.753

Figure 1. BET Sorption isotherms of carrot and potato at different PEF treatment strength.

Figure 2. Carrot and potato force vs. distance curves for different hydration levels ($a_w$).

## Declaration of interests

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☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: