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

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Abstract:	<p>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).</p>
Suggested Reviewers:	Francisco Barba francisco.barba@uv.es
Opposed Reviewers:	
Response to Reviewers:	

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](#)

- Potato and carrot treated at 3 PEF intensities and dried at 60°C.
- 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

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

3
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14
15 **Abstract**

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

28
29 **Keywords:** Mechanical properties modelling, Pulsed electric field, Dried vegetables, Sorption
30 Isotherms

31
32
33
34

35 **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, °C
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
Δw	Weight difference

36 **1. Introduction**

37 The food sector as a whole is faced with major challenges that arise from economic and environmental
38 changes, changes in lifestyle, global increases in food consumption, and attitudes of society toward
39 the consequences of food production associated with environmental, social, and economic issues,
40 often captured within the term of sustainability (Fritz & Schiefer, 2008). Thus, the sector needs to
41 innovate in organisational relationships that reach beyond innovations in process improvement by
42 building on the innovation potential inherent in enterprise networks and their flexibility in responding
43 to customers and their demands (Pittaway, Robertson, Munir, Denyer, Neely, 2004). Mathematical
44 modelling is important regarding the scale-shift of the process, from the laboratory to the industrial
45 scale and also allows the phenomena involved in the transformation of food matrices to be
46 parameterised. In food science, transformation processes are integrations of multiple phenomena
47 which result in a complex systems consisting of a large number of interacting microbiological and/or
48 physicochemical components, whose aggregate activities are nonlinear and are responsible for the

49 changes of product properties. Confronted with this complexity, decisions related to the management
50 of such processes increasingly rely on mathematical models that represent the available knowledge
51 about involved phenomena, and that are able to simulate the different transient and equilibrium states
52 over time (Baudrit, Wuillemin, Perrot, 2013).

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

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

79 PEF treatment can be used as a pre-treatment to enhance drying. Hot air dryers are the most
80 widespread dryers in different industries, not only for food and agriculture applications but also for
81 paper, textile, and chemical ones (Mousakhani-Ganjeh et al., 2021). However, these dryers are
82 characterised by a high energy consumption, low efficiency, and a high impact on the quality of the

83 final product. The reduction of drying time by PEF pre-treatment depends on the applied parameters,
84 drying method, and raw material. Therefore, there is no standard PEF application method, and the
85 effectiveness of electroporation depends on many processing-related parameters. Among parameters,
86 electric field strength and energy input are the most frequently modulated ones and could be used to
87 compare results of different research groups (Barba et al., 2015).

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

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

99

100 **2. Material and methods**

101 **2.1. Material and samples preparation**

102 Potatoes (*Solanum tuberosum* var. Agata) and carrots (*Daucus carota* var. Amsterdam) were
103 purchased from the local market in Cesena, Italy and stored at 10°C until processing. Fresh potato,
104 and carrot water content was of 5.7 ± 0.6 and 9.8 ± 0.4 kg [water] kg [dry mass], respectively (AOAC
105 official method n. 934.06). Samples were cut into cylindrical shape (length: 10.0 ± 0.1 mm; diameter:
106 9.0 ± 0.1 mm) by using a manual cork borer.

107

108 **2.2. Pulsed electric field and air-drying treatments**

109 Twenty pieces of potatoes and carrots per treatment were placed in a $50 \times 50 \times 50$ mm treatment
110 chamber. Each piece had a weight of 1.3 ± 0.2 g. Tap water (515 ± 20 $\mu\text{s cm}^{-1}$ conductivity) was used
111 to fill up the treatment chamber in a 1:2 ratio, sample to water. The conductivity was measured using
112 an electrical conductivity meter mod. Basic 30 (Crison Instrument, Spain). A pulse generator mod.
113 S-P7500 60A 8kV (Alintel srl., Bologna, Italy) was applied for PEF treatment. Near-rectangular
114 shaped pulses, with a pulse width of 10 μs and frequency of 100 Hz were applied, as previously
115 reported (Castagnini et al., 2020; E. Iaccheri et al., 2021). 0.5, 1 and 1.5 kV cm^{-1} field strength were
116 tested at 25°C. Controls non-PEF treated samples (0 kV) were also prepared. The total treatment time

117 was set to 1 s. The calculated energy specific intake (W_T) for the samples treated at 0.5, 1 and 1.5 kV
118 cm^{-1} was 0.121, 0.483 and 1.086 kJ kg^{-1} respectively. The W_T for rectangular pulse was calculated as
119 follows:

120

$$121 \quad W_T = \frac{n}{m} \int_0^\infty U(t) \cdot I(t) dt \quad (1)$$

122

123 Where n is the number of pulses applied, m is the mass of treated sample, $U(t)$ is the voltage across
124 the treatment chamber and $I(t)$ is the current through the treatment chamber (Raso et al., 2016).

125 Immediately after PEF treatment, carrot and potato samples were dried at 2 m s^{-1} in a tray air drier at
126 60°C (mod. CLW 750 TOP+, Pol-Eko- Aparatura SP.J., Poland), with transverse airflow, an air
127 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
128 hours). The samples were putted in perforated trays. The a_w was measured with a dewpoint
129 hygrometer (Aqualab, Decagon Devices Inc., Pullman, WA, USA). The treatment was carried out
130 three times.

131

132 2.3. Sorption isotherm

133 The traditional saturated salt slurry method was used to reach different thermodynamic equilibrated
134 relative humidity values. Firstly, air dried samples were conditioned by putting them into a desiccator
135 with P_2O_5 to reach a complete dehydration, by monitoring three consecutive constant weight
136 ($\Delta w < 0.0005 \text{ g}$). Afterwards, carrot and potato samples were positioned in the hermetically closed
137 desiccator (DES 2000) containing the saturated salt solutions which correspond to the required a_w
138 (0.113 LiCl; 0.225 $\text{CH}_3\text{CO}_2\text{K}$; 0.331 MgCl_2 ; 0.432 K_2CO_3 ; 0.576 NaBr and 0.753 NaCl). The
139 thermodynamic equilibrium took place at $22 \pm 1^\circ\text{C}$. Each hydration experiment comprised a reference
140 sample and samples treated at specific field strengths (0.5, 1 and 1.5 kV cm^{-1}). Samples were
141 periodically checked until a constant weight for three consecutive measurements were reached ($\Delta w <$
142 0.0005 g). The equilibrium was also verified by a_w measurement. Water content was gravimetrically
143 determined by using oven drying at 70°C until reaching steady mass, and herein expressed on dry
144 matter basis (AOAC 934.06).

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

$$147 \quad X = \frac{V_m C a_w}{(1-a_w)(1+(C-1)a_w)} \quad \text{eq. 2}$$

148

$$149 \quad X = \frac{V_m C k a_w}{(1-k a_w)(1-k a_w + C k a_w)} \quad \text{eq. 3}$$

150

151 Where X is the water content (g [water] 100 g⁻¹ [solids]), a_w is the water activity, V_m is the monolayer
152 water content (g [water] 100 g⁻¹ [solids]), k is a constant related multilayer molecules interaction with
153 the sorbent and C is the constant related to monolayer sorption heat (Barbosa-Canovas & Fontana,
154 2020).

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

161

162 **2.4. Mechanical properties**

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

170

171 **2.5. Modelling of texture properties**

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

$$174 \quad Y_{(a_w)} = \frac{Y_0}{1 + \exp\left(\frac{a_w - a_{wc}}{b}\right)} \quad (4)$$

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

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

$$180 \quad Y_{(a_w)} = \frac{Y_0 - Y_r + K a_w^n}{1 + \exp\left(\frac{a_w - a_{wc}}{b}\right)} + Y_r \quad (5)$$

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

183

184 **2.6. Statistical analysis**

185 The BET and GAB equations were applied to moisture content and water activity experimental data
186 (Statistica 7.0 (Statsoft Inc. - www.statistica.com)) and Marquardt algorithm (Mathematics, 1977).

187 The algorithm calculates the root mean square error (RMSE) values were employed to evaluate
188 model performance (Eq. (6)):

$$189 \quad RMSE = \sqrt{\frac{\sum_{i=1}^n (\hat{y}_i - y_i)^2}{n}} \quad (6)$$

190 \hat{y}_i are predicted values, y_i are observed values and n is the number of observations.

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

195

196 **3. Results and discussion**

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

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

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

218 Table 1. Sorption isotherm parameters for BET and GAB equations and related coefficient of
 219 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

220

221 BET and GAB equations belong from the same family, although BET can be more suitable for
 222 monolayer value estimation. The monolayer value has been found to be crucial for stability
 223 description, particularly for dried products. Carrot monolayer value estimated with BET increase as
 224 a function of electric field strength. Accordingly, PEF treatment on carrot samples at high electric
 225 field strength could led more site for water H-bonding. This behaviour could be also compatible with
 226 the type III of sorption isotherm shape, characterised by adsorption phenomena accounting for solid
 227 surface interactions (Barbosa-Canovas & Fontana, 2020). This effect could be also considered, as
 228 PEF is widely recognised for cell membrane disruption enhancement (Lebovka, Bazhal, Vorobiev,
 229 2002; Lebovka et al., 2007; Liu, Grimi, Lebovka, Vorobiev, 2018). An opposite trend was verified
 230 for potato samples; monolayer values does not change because of PEF treatment. Sorption isotherms
 231 of potato were characterized by type II shape, more related to absorption mechanisms, as water
 232 internalization into solids (Barbosa-Canovas & Fontana, 2020).

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

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

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

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

250

251

252 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

253

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

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

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

268

269

270 Table 3. Maximum force (N) at different PEF treatments (mean values and standard deviation).
 271 Letters indicates difference among treatments means, p-level <0.05. No difference among means does
 272 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 ± 9 ^a	42 ± 8 ^{ab}	35 ± 10 ^b	28 ± 2 ^c
	0.225	44 ± 11 ^a	44 ± 4 ^a	32 ± 9 ^{ab}	29 ± 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 ± 8 ^a	31 ± 8 ^a	46 ± 7 ^b	48 ± 11 ^b
	0.225	24 ± 6 ^a	31 ± 3 ^{ab}	41 ± 9 ^{bc}	46 ± 11 ^c
	0.331	21 ± 7 ^a	26 ± 6 ^a	39 ± 8 ^b	48 ± 4 ^b
	0.432	19 ± 5 ^a	24 ± 6 ^a	40 ± 11 ^b	36 ± 9 ^b
	0.576	18 ± 6 ^a	22 ± 4 ^{ab}	31 ± 8 ^{bc}	36 ± 9 ^c
	0.753	19 ± 2 ^a	17 ± 3 ^a	24 ± 4 ^b	24 ± 5 ^b

273

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

283

284 4. Conclusions

285 GAB and BET equations were applied to experimental data to understand sorption behaviour as a
 286 function of PEF treatment for dried carrot and potato, respectively. High determination coefficient of
 287 0.980 for GAB and 0.977 for BET were obtained confirming the ability of both models to accurately
 288 describe the sorption isotherm of foodstuff. BET and GAB modelling permitted to classify carrot and
 289 potato isotherms of type III and type II shape, respectively. Carrot monolayer value estimated by the

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

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421

Figure 1

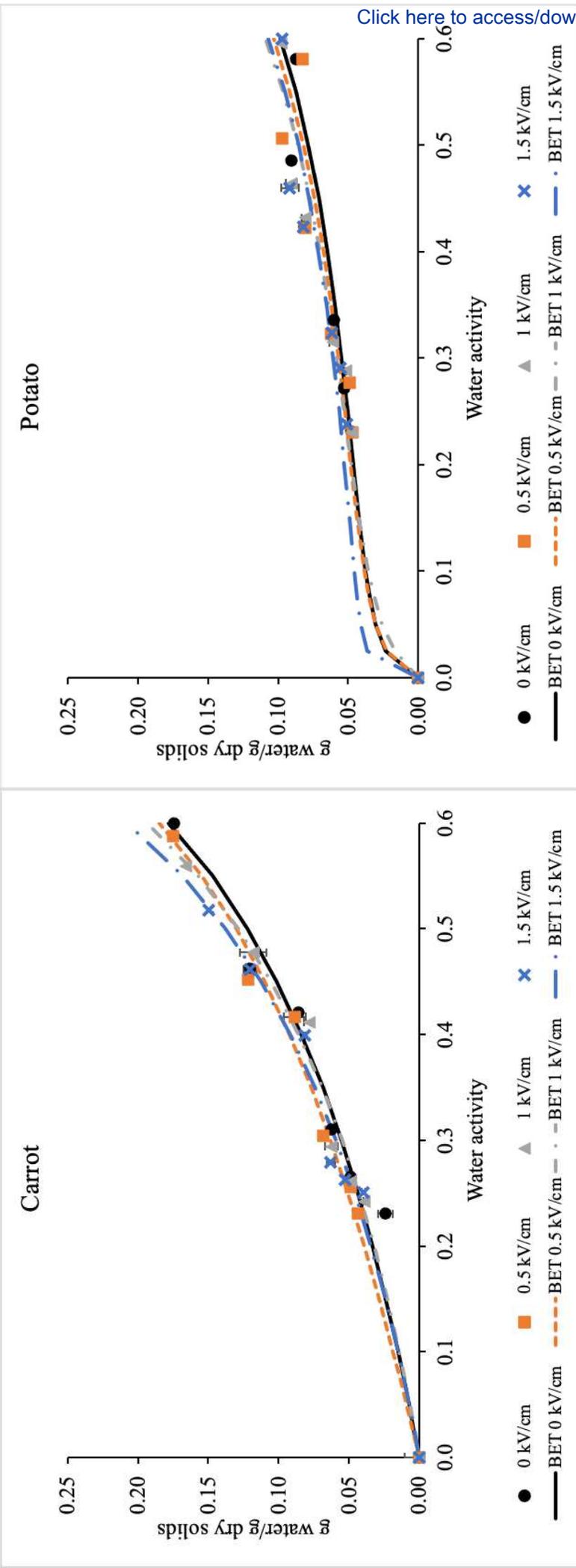


Figure 2

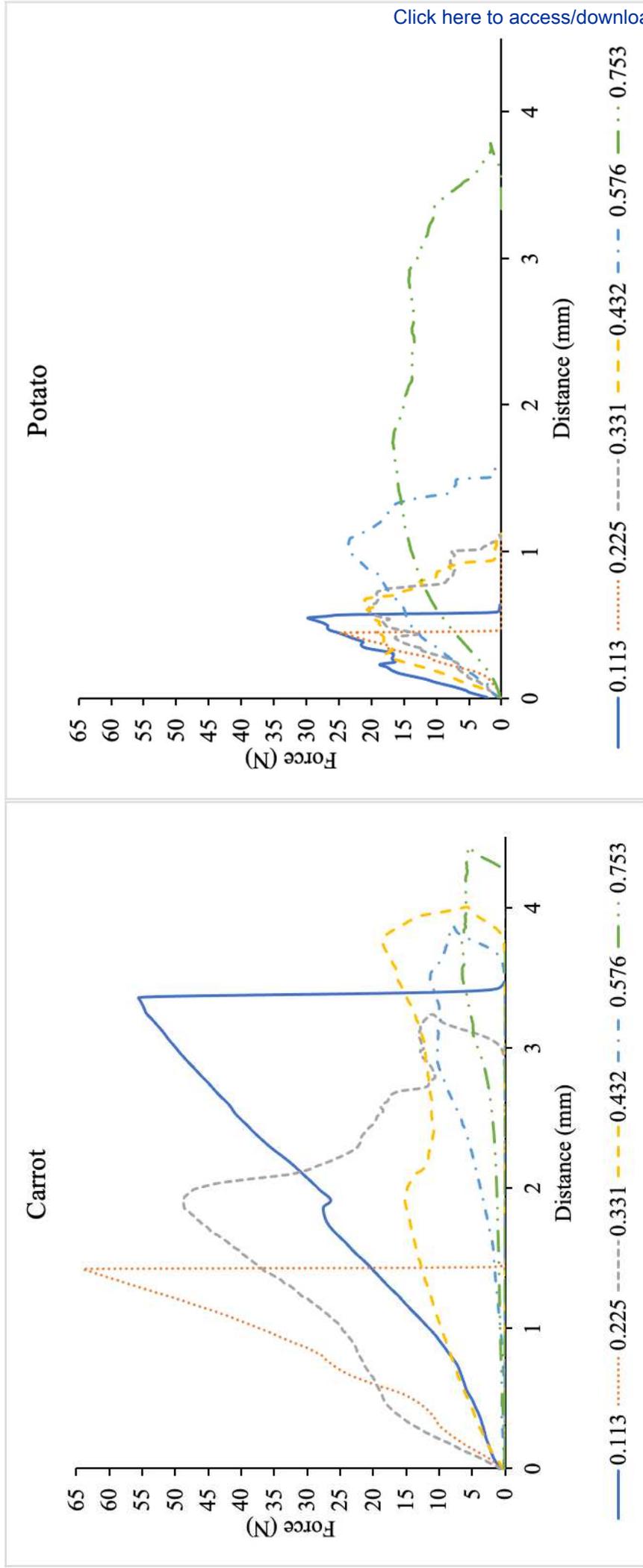


Figure 1. BET Sorption isotherms of carrot and potato at different PEF treatment strength.

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: