Hindawi
Journal of Food Processing and Preservation
Volume 2023, Article ID 8172255, 11 pages
https://doi.org/10.1155/2023/8172255

Research Article

Pulsed Electric Field Treatment Application to Improve Product Yield and Efficiency of Bioactive Compounds through Extraction from Peels in Kiwifruit Processing

Ivan Shorstkii[1], **Corinna Stuehmeier-Niehe**[2], **Maxim Sosnin**[1], **Emad Hussein Ali Mounassar**[1], **Martina Comiotto-Alles**[2], **Claudia Siemer**[2], **and Stefan Toepfl**[2]

[1]*Advanced Technologies and New Materials Laboratory, Kuban State Technological University, Moskovskaya 2, 350072 Krasnodar, Russia*
[2]*Elea Vertriebs-und Vermarktungsgesellschaft mbH, Prof. von Klitzing Str. 9, 49610 Quakenbrück, Germany*

Correspondence should be addressed to Claudia Siemer; c.siemer@elea-technology.com

Received 27 February 2023; Revised 29 April 2023; Accepted 2 May 2023; Published 17 May 2023

Academic Editor: Charles Haminiuk

The kiwifruit processing industry is focused on product yield maximization and keeping energy costs and waste effluents to a minimum while maintaining high product quality. In our study, pulsed electric field (PEF) pretreatment enhanced kiwifruit processing to facilitate peelability and specific peeling process and enhanced valorization of kiwifruit waste. PEF optimization was applied to obtain the best treatment parameters. A 3^2 factorial design of response surface methodology was applied to find the effect of time elapsed after PEF treatment and the PEF-specific energy input on specific peeling force and kiwifruit firmness as response criteria. Under the optimized condition, the specific peeling force decreased by 100, and peelability increased by 2 times. The phenolic content and antioxidant capacity of PEF-treated kiwifruit bagasse were 5.1% and 260% richer than the control sample. Overall, the optimized PEF pretreatments incorporated into kiwifruit processing led to decreased energy demand and increased productivity.

1. Introduction

The juice and smoothie market is continuously growing, and consumers are increasingly drawn to high-quality beverages with fresh-like properties that are rich in vitamins, dietary fiber, and other beneficial nutrients [1]. The kiwifruit, originally from China and belonging to the family *Actinidiaceae*, is currently high in demand for the production of juices and smoothies [2]. Apart from the pleasant organoleptic attributes [3], kiwifruit is high in vitamin C and is a natural source of antioxidants [4, 5].

The relatively high water content (83%), the presence of phenolic compounds, and the antioxidant capacity make the kiwifruit a particularly attractive option for juice processing [6] Nevertheless, processing parameters can influence the physicochemical and microbiological characteristics of the final juice product, which, in turn, can impact the production yield and the storage life of the juice, respectively [7–9]. Besides, the kiwifruit, tomatoes, peaches, and oranges are also popular choices for juice production due to their high water and vitamin contents [10].

Fruit peeling is a common step in the juice production process. Conventionally, abrasive peeling methods are used, but they often result in a high waste percentage and massive yield loss. Fruit ripeness and time of harvest can also affect the efficiency of the peeling process [11]. In addition, there has been a growing interest in the valorization of the kiwifruit peels itself, as it is a source of numerous high-value phytoconstituents with beneficial properties and potential applications in the food and pharmacological fields, among others [12].

A promising approach is the use of pulsed electric fields (PEF) for the gentle peeling of fruit before juice production.

PEF is an innovative technology that can be used to extend the shelf life of fresh liquid products with minimal impact on the quality [13–15]. Industrial-scale PEF systems are available with designs that have been validated to meet hygienic requirements and regulatory standards such as hazard analysis critical control points (HACCP). For this purpose, the critical PEF process parameters have been identified and established. A PEF system is typically comprised of a pulse generator and a treatment unit, both of which can be easily integrated into an existing production line [16].

The main target of PEF is the cell membrane. It is composed principally of phospholipids which behave as a barrier for mass transfer and are responsible for maintaining cell homeostasis. Naturally, there is an accumulation of charged particles on either side of the cell membrane, creating the so-called transmembrane potential [17]. Applying an external voltage can increase this potential and cause pore formation. Depending on the applied field strength, the pores can be reversible or irreversible. With regard to peeling, the benefits of PEF have already been observed for tomatoes [18]. In this study, the influence of different PEF treatment settings on the peeling of kiwifruit, as well as on the physicochemical parameters including pH, °Brix, water activity, phenolic compound, colour, and antioxidant capacity, was investigated. The ultimate objectives were to improve product yield, maximize beneficial health effects, and explore peel waste valorization by parameter optimization.

2. Materials and Methods

2.1. PEF Treatment. Kiwifruits from Italy were purchased from a local supermarket and sorted to ensure the absence of defects. The average weight of the kiwifruit was 85.1 g. A PEF system (PEFPilot™ Dual, Elea Vertriebs-und Vermarktungs mbH, Quakenbrück, Germany) with a stainless steel chamber, equipped with parallel plate electrodes and an electrode gap of 10 cm, was used for the experiment. Whole kiwifruits were suspended in tap water and placed inside the PEF treatment chamber. The applied pulses were monopolar with rectangular decay. The effect of the different PEF treatments was evaluated on the kiwifruit firmness, peeling performance, and physicochemical characteristics. Specific energy input, W_{spec}, and time pause after PEF treatment were used as variables. For physicochemical analysis, PEF settings of 4 pulses, 1 kV/cm (field strength), and 1 kJ/kg (specific energy) were used.

2.2. Kiwifruit Firmness. The firmness of kiwifruit was evaluated using a texture analyzer (TA.XT plus, Stable Micro Systems, UK) through a compression test. Unpeeled kiwifruits were sliced into 1 cm thickness. Each slice was placed horizontally on the texture analyzer and compressed to a distance of 5 mm using a 25 mm multiple probes (P/6, Stable Micro Systems, UK) moving at a forward speed of 5 mm/s (Figure 1(a)).

2.3. Kiwifruit Peeling Performance. The peeling of the kiwifruit was performed mechanically using the TA.XT plus Texture Analyzer (Stable Micro Systems, Godalming, Surrey, UK) fitted with the Meullenet-Owens Razor Shear (MORS) blade with a pretest speed of 1 mm/s, a test speed of 5 mm/s, and a defined distance of 14 mm. The selected precut area on the kiwifruit skin was removed, and a specific peeling force was calculated. Figure 1 demonstrates the peeling procedure (Figure 1(a)) and peeled kiwi tissue (Figure 1(b)).

The specific peeling force (F_p) was calculated from the peeling energy and the area of the peeled skin as follows:

$$F_p = \frac{E_p}{S}, \tag{1}$$

where E_p is the peeling energy from the texture analyzer and S is the area of the peeled skin sample, m^2.

To determine the area of the peeled skin, the sample was photographed on a whiteboard with a tripod positioned at a fixed distance. Briefly, to measure the area, the skin picture was surrounded by a perimeter, and the S value was automatically calculated. Afterwards, the pictures were analyzed with ImageJ (v 1.52e), a Java-based image processing program.

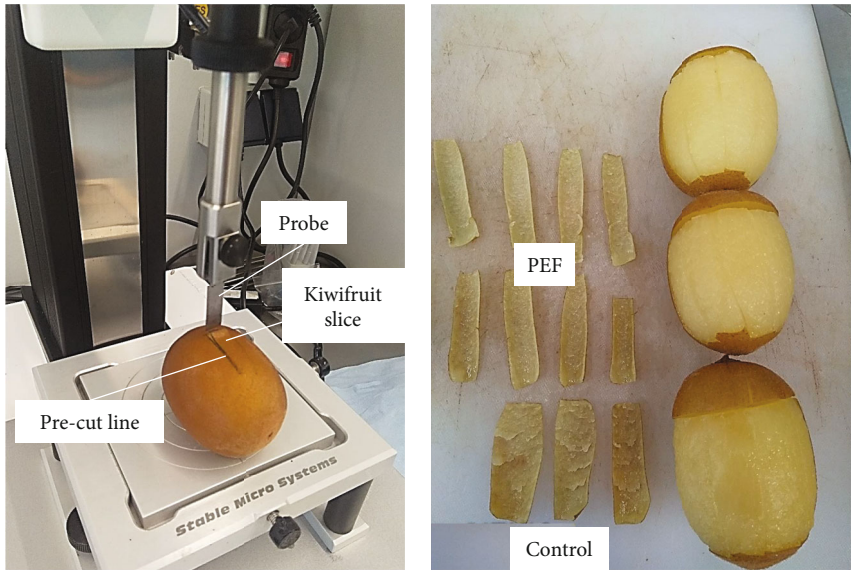
Peelability was used to determine the degree of peel removal and calculated as removed peel area per unit weight (cm^2/g). Therefore, to determine the peelability value, the peeled skin sample was also weighted on a digital scale (Kern PCB 10000-1, Balingen, Germany).

2.4. Experimental Design and Process Optimization. The optimization of PEF treatment parameters was conducted using a 3^2 factorial design of response surface methodology as described earlier [19]. A total of 13 experiments were planned according to the central composite design (CCD). Each variable was set at three different levels (Table 1). The first 8 experiments were performed at noncenter points to obtain an overview, and the final 5 experiments were performed at the center points. During a pilot study of PEF application for peeling [18], two main factors were identified that affect the kiwifruit peeling performance: the time elapsed after PEF treatment before peeling (X_1) and the PEF-specific energy input (X_2).

The response criteria were selected based on previous works [20–22]. Specific peeling force (Y_1) as described in Section 2.2 was used as the first response criteria. To preserve the shape and texture of the final peeled kiwifruit, firmness (Y_2) was set as the second criteria. In the subsequent processing steps after peeling, it is important to maintain materials with high firmness [21]. The texture preservation effect of PEF could be attributed to the overall minimal thermal load since both the treatment time and temperature are kept to a minimum during processing. Skin ratio or peelability (Y_3) based on a manual peeling assessment method [23] was set as the last response criteria as it can influence the profit margins and the return of investment for the equipment.

All factors are compatible and do not correlate with each other. The polynomial model of the second degree was used for the two-factorial experimental design and can be written as [24]

$$Y = \mu_0 + \sum_{i=1}^{z} \mu_i X_i + \sum_{i=1}^{z} \mu_{ii} X_i^2 + \sum_{i \le j}^{z} \mu_{ij} X_i X_j, \tag{2}$$



(a) (b)

Figure 1: Kiwifruit peeling procedure based on texture analyzer system (a) and peeled fruit (b).

Table 1: Input data for 3^2 factorial designs.

Planning conditions	Coded value	Factors	
		X_1 Time pause after PEF treatment (s)	X_2 Specific energy input, W_{spec} (kJ/kg)
Main level	0	40	1
Interval	Δ	20	0.5
Maximal level	+1	60	1.5
Minimal level	-1	20	0.5

where Y is the response function (Y_1, specific peeling force; Y_2, kiwifruit firmness; and Y_3, peelability), μ_0 is a free term of the equation (overall mean), X is the scaled values of the factors determining the response function, μ is the regression coefficients, determining the nonlinearity of the output parameter from the considered factors, i and j are the factor indexes, and z is the number of factors.

The objective of the process optimization was formulated: to find a range of parameters from the factorial design which provides a minimal specific peeling force, maximizes the kiwifruit firmness, and minimizes the kiwifruit waste mass. This can be expressed as follows:

$$\begin{gathered} q = q(Y_1, Y_2, Y_3) \underset{x \in D}{\longrightarrow} \text{opt}, \\ D : Y_1(X_1, X_2) \underset{x \in D}{\longrightarrow} \min, \\ Y_2(X_1, X_2) \underset{x \in D,}{\longrightarrow} \max,\ Y_3(X_1, X_2) \underset{x \in D,}{\longrightarrow} \min, \\ Y_i \geq 0, i = \overline{1,3}\,; X_j \leq [-1\,;1], \\ j = \overline{1,2}, \end{gathered} \tag{3}$$

where q is a target function and D is a set of parametric functions.

2.5. Kiwifruit Characteristics

2.5.1. Preparation of Kiwifruit Powders and Extracts. The PEF-treated and control samples were manually peeled using stainless steel knives to separate the insides of the fruit (bagasse) from the skin. Untreated kiwifruits were used as control. The bagasse and skin samples were oven dried at 35 ± 5°C for at least 72 hours. The samples were subsequently milled in a Moulinette (Moulinex, Alencon, France) into fine powders. The powders were stored at -18°C till further use. Extracts were made from the samples by mixing the powder at 1 : 10 (w/v) with 80% ethyl alcohol and shaking at 200 rpm for 2 hours at room temperature (shaking incubator, Eppendorf, Germany). The mixture was centrifuged and filtered through a Whatman filter No. 2. The collected extracts of kiwifruit skin and bagasse were packed and stored in a freezer at -18°C.

2.5.2. Determination of pH and Water Activity. To prepare the samples for pH determination, the powders were mixed with distilled water at a ratio of 1 : 10 and stirred until homogenous. The pH was measured using a pH meter (Lab865, SI Analytics, Weilheim, Germany). To determine the water activity (a_w), an average of 3 g of powder was used and analyzed at room temperature in a water activity meter

(AQUALAB 4TE, METER Group, Inc., USA). The analyses were performed in two biological replicates with three technical replicates each.

2.5.3. Colour Measurement in $L^*a^*b^*$ Units and Brix Measurement. A bench-top spectrophotometer (CM-5, Konica Minolta, Tokyo, Japan) was used to assess the colour difference between the PEF-treated samples and the control. The analysis was performed in cuvettes in three technical replicates. The powdered kiwi samples were rehydrated in tap water. The refractive index (°Brix) of the rehydrated samples was measured in two biological replicates using a refractometer (HI 96801, Hanna Instruments, Frankfurt, Germany).

2.5.4. Determination of Total Phenolic Compounds (TPC). The method was performed according to Soquetta et al. [25] with some modifications. To estimate the phenolic compounds in the kiwi skin and bagasse, the extracts were diluted in a volumetric flask in 80% ethanol at a ratio of 1 : 100 (*v*/*v*) for the kiwi skin and 1 : 50 (*v*/*v*) for the kiwi bagasse. 0.2 ml of this solution was mixed with 1 ml of 2 N Folin-Ciocalteu reagent (diluted 1 : 10). After being kept for 8 min in the dark, 0.8 ml of 7.5% sodium carbonate solution (Na_2CO_3) was added. After incubation at 25°C for 2 h, the absorbance was measured at 765 nm in a UV/Vis spectrophotometer (GeneQuant™ 1300, Biochrom, USA). A standard curve was created for quantification ($y = 0.1374x + 0.4972$, $R^2 = 0.9673$) using gallic acid ranging in concentrations from 0 to 75 mg/l. The values were expressed in mg of gallic acid equivalent per 100 g of powder. The experiments were performed in two biological replicates with two technical replicates each.

2.5.5. Determination of Antioxidant Capacity. The antioxidant capacity was determined according to the method of Re et al. [26] with some modifications. Measurements were performed in a bench-top spectrophotometer (CM-5, Konica Minolta, Tokyo, Japan). A stock solution of 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS)) was prepared in water to a 7 mM concentration. ABTS radical cation ($ABTS^{\bullet+}$) was produced by reacting the ABTS stock solution with 2.45 mM potassium persulfate (final concentration) and allowing the mixture to stand in the dark at room temperature for 12-16 hours before use, to allow incomplete oxidation of the ABTS. For the study of the antioxidative capacity of the kiwi samples, the $ABTS^{\bullet+}$ solution was diluted with ethanol (98% p.a.) to an absorbance of 0.7 at 734 nm. A prepared stock solution of Trolox (Trolox® equivalent antioxidative capacity) was diluted from 10 mM to create calibration standards with final concentrations of 0, 50, 100, 150, and 200 μM Trolox. 1 ml of the diluted $ABTS^{\bullet+}$ solution ($OD_{734} = 0.7$) was added to 100 μl of either the kiwi extracts or to the Trolox standards in ethanol. The absorbance reading was taken exactly 6 minutes after the initial mixing. Appropriate solvent blanks were run in each assay. All determinations were carried out in two technical replicates. The percentage inhibition of absorbance at 734 nm was calculated as a function of the concentration of antioxidants and of Trolox for the standard reference data.

2.6. Statistical Analysis. All measurements of the abovementioned characteristics were performed in at least five replicates. The peeling experimental design data were analyzed using the Design Expert software (version 13.0.5.0, Stat-Ease Inc., USA). Multiple regression analysis was used to fit the model to the experimental data, and the output was represented by an equation. The adequacy of the developed models was evaluated using the *F*-ratio and coefficient of correlation (R^2). Statistical evaluation of the physicochemical properties was performed by one-way ANOVA, using SigmaPlot (version 14).

3. Results and Discussion

3.1. Improvement in Peeling of Whole Kiwifruit. PEF treatment modified the structure of kiwifruit tissue by damaging the cell membranes and causing tissue softening, which helps to facilitate peel removal. During a preliminary study, two main factors were identified that affect the peeling of kiwifruit: the PEF-specific energy input and the time pause before peeling after the PEF treatment. Further analysis according to the factorial design was done for a time pause of 40 s after the PEF treatment. The dynamics of kiwi peel removal are presented in Figure 2.

For each setting, the maximum specific peeling force was defined from the graph and summarized in Table 2. Based on the experimental results, PEF-specific energy input appeared to significantly influence the kiwifruit-specific peeling force. When the specific energy input was less than 0.5 kJ/kg, skin removal from kiwifruit was still difficult, as demonstrated by the high peeling force. Peel removal of the control sample was aborted due to breakage of the kiwifruit skin. From the applied specific energy levels W_{spec} of greater than 0.5 kJ/kg, the skin started to peel off very easily. An additional increase of the specific energy further decreased the peeling force but not to a significant degree. This can be explained by a higher electroporation effect on the cell membrane and greater mass transfer [27].

From the author's point of view, the improvement in peelability could be explained by the migration of water from the mesocarp region under the kiwifruit skin as a result of electropermeabilization. This led to a pressure difference across the kiwifruit skin, reducing the surface resistance and facilitating its removal. The mechanism of water migration is depicted in Figure 3. The internal mass transfer was activated due to the turgor pressure of plant cells. Similar behavior has been reported by several authors for tomato tissue and grapes [20, 28].

The results of our study demonstrated that the PEF treatment of kiwifruit produced less peeling loss as compared to the control (Table 2). The low specific energy level of PEF treatment (0.3 kJ/kg) was not sufficient to enhance the peelability of kiwifruit. Increasing the specific energy, thereby increasing the number of applied pulses, improved the peelability and decreased peeling loss.

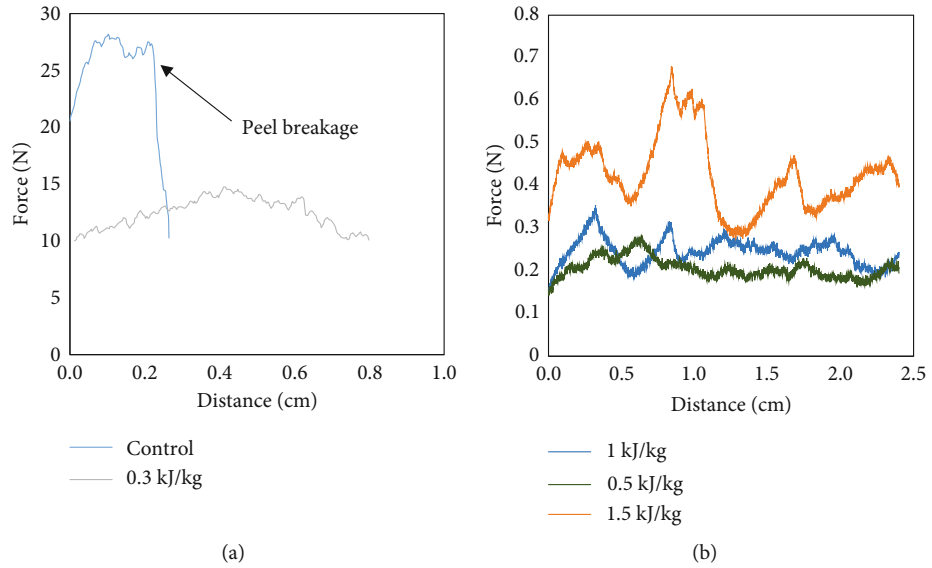


Figure 2: A specific force graph of instrumental kiwifruit peeling analysis (TPA) for control and PEF-treated samples at different specific energy input levels: (a) control and 0.3 kJ/kg and (b) 0.5-1.5 kJ/kg.

Table 2: Physical and mechanical properties of kiwifruit treated by PEF.

	Specific peeling force (N/cm)	Peelability (cm^2/g)	Kiwifruit slice firmness (N)
Control	28.3 ± 3.35	0.2 ± 0.03	183 ± 7.13
PEF (0.3 kJ/kg)	14.8 ± 1.12	0.18 ± 0.03	115 ± 4.62
PEF (0.5 kJ/kg)	0.29 ± 0.03	0.09 ± 0.02	80 ± 4.15
PEF (1 kJ/kg)	0.35 ± 0.04	0.11 ± 0.01	92 ± 3.73
PEF (1.5 kJ/kg)	0.68 ± 0.03	0.089 ± 0.01	38 ± 3.90

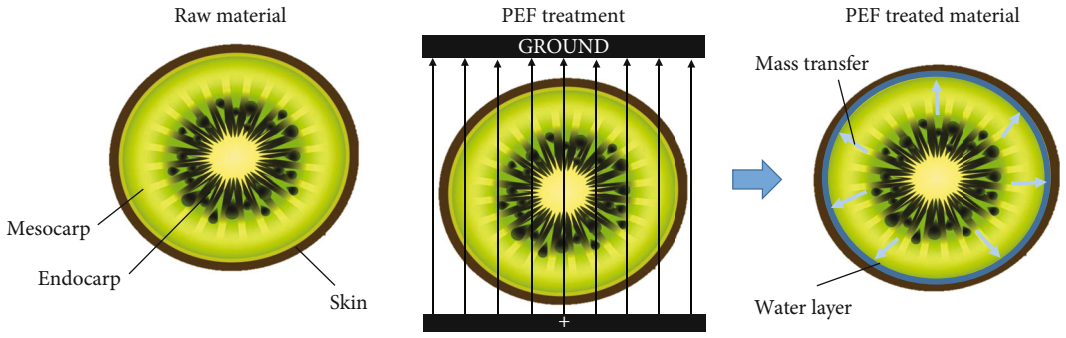


Figure 3: Water migration mechanism in kiwifruit caused by pulsed electric field treatment.

3.2. Kiwifruit Firmness after PEF Treatment. The kiwifruit firmness is indicative of its ripeness [29] and is often used to determine the suitability of the fruit for critical steps in postharvest processing, including peeling [30]. The experimental results of the strain force produced by the texture analyzer are presented in Figure 4. The different responses exhibited by the fruit texture as a result of the maturity stage demonstrated its nonhomogenous composition. As stated by other researchers, the kiwifruit is composed of four major tissue types (rind, aril, seed, and spongy white tissues), all with different mechanical properties [29, 31–33]. The smoothed curves in Figure 4 represent the global behavior of the force-deformation [34]. The kiwifruit slices pretreated by PEF as well as the control presented regular force-deformation curves. The compression force data are summarized in Table 2, which shows a tendency for force reduction with increased PEF-specific energy input.

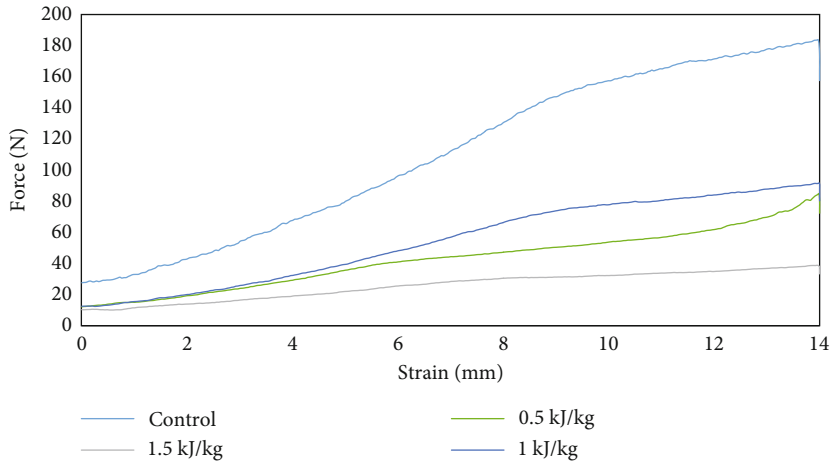


Figure 4: Puncture force via deformation curve of kiwifruit samples pretreated by PEF.

3.3. Peeling Optimization. Using the regression analysis function in the Design Expert software, the following regression equations for Y_1, Y_2, and Y_2 were obtained:

$$Y_1 = 3.65 - 0.081X_1 - 2.256X_2 + 0.0145X_1X_2 + 0.00068X_1^2 + 0.549X_2^2,$$
$$Y_2 = -18.54 + 0.769X_1 - 227.7X_2 - 0.125X_1X_2 - 0.0078X_1^2 - 130.55X_2^2,$$
$$Y_3 = 1.875 - 0.046X_1 + 0.688X_2 - 0.0025X_1X_2 + 0.00044X_1^2 - 0.439X_2^2. \quad (4)$$

From the obtained equations, it was possible to deduce the most significant factor for the peeling performance of the kiwifruit, namely, the specific energy input (X_2). A negative sign before the coefficient with linear terms indicates that when the input parameter increases, the value of the output parameter decreases. The data obtained from the 13 experiments and the peeling optimization model (Equation (3)) enabled the calculation of the response variables within the selected intervals of input factor variation (Figure 5). Optimum conditions were determined based on minimizing peeling assessment while maximizing kiwifruit firmness (Figure 6).

For all input factors (X_1 and X_2), differences in optimization criteria are significant. By using response surface methodology and optimization task from Equation (3), the optimized range of factors was obtained and was equal to $X_1 = 0.9 - 1.1$ kJ/kg and $X_2 = 42 - 48$ s and is shown in Figure 5. The standard deviation is less than 4%.

Thus, the optimization task was solved, which made it possible to pinpoint the ideal range of input factors (time elapsed after PEF treatment and the PEF-specific energy input) according to the three peeling performance criteria.

3.4. pH and Water Activity (a_w). To determine the influence of the PEF treatment on pH and water activity, measurements were performed on the kiwi extracts and powders. The results are shown in Table 3.

These results were consistent with those reported previously for kiwifruit, as they have a pH value of 3.3 to 4.1 [5]. Many researchers have observed no variation in the pH value after different PEF treatments in different fruit and vegetable tissue powder [35, 36]. In our study, the pH of the PEF-processed samples decreased slightly in comparison with the control sample. No significant difference was observed between the pH values of the extract.

For the water activity, a statistically significant difference ($P = 0.001$) was observed between the PEF bagasse sample and the control bagasse sample. The application of electric fields increased the electrical energy of the cell membrane surface (protoplast and tonoplast) and of the cell wall. As a result, there was more surface-free energy available for molecular adsorption. As the number of layers of adsorbed water molecules increased, the number of free water molecules in the liquid phase decreased. This effect would therefore explain the observed lower water activity in the PEF-treated bagasse [37].

In contrast, the water activity of PEF-pretreated kiwifruit tissue rose by 32.67% to a value of 0.59 ± 0.004. It is suggested that PEF pretreatment reduces the water activity in the skin tissue. Due to the pore formation, the sugar molecules contained in the kiwifruit skin can diffuse to its surface by capillary forces immediately after treatment. At the surface, sugar molecules can form a film that prevents moisture uptake and a steep increase in water activity [35]. A similar reaction of water activity enhancement was observed in apple tissue [35].

3.5. Colour Measurements in $L^*a^*b^*$ Units and Brix. To determine the differences in the colour and the Brix values of the kiwi samples, analyses were performed in three biological replicates for the colour and in two biological replicates for the Brix, with three technical replicates each. A statistically significant difference ($P = 0.001$) was observed for the L^* and the b^* values, indicating a difference in the lightness (L^* value) and in the yellow-blueness (b^* value) of the PEF-treated samples compared to the control. There was no significant difference in the green-redness area (a^* value) between the samples. Table 4 presents the optical properties (in CIE $L^*a^*b^*$ scale) of PEF-pretreated and control kiwifruit skin and bagasse.

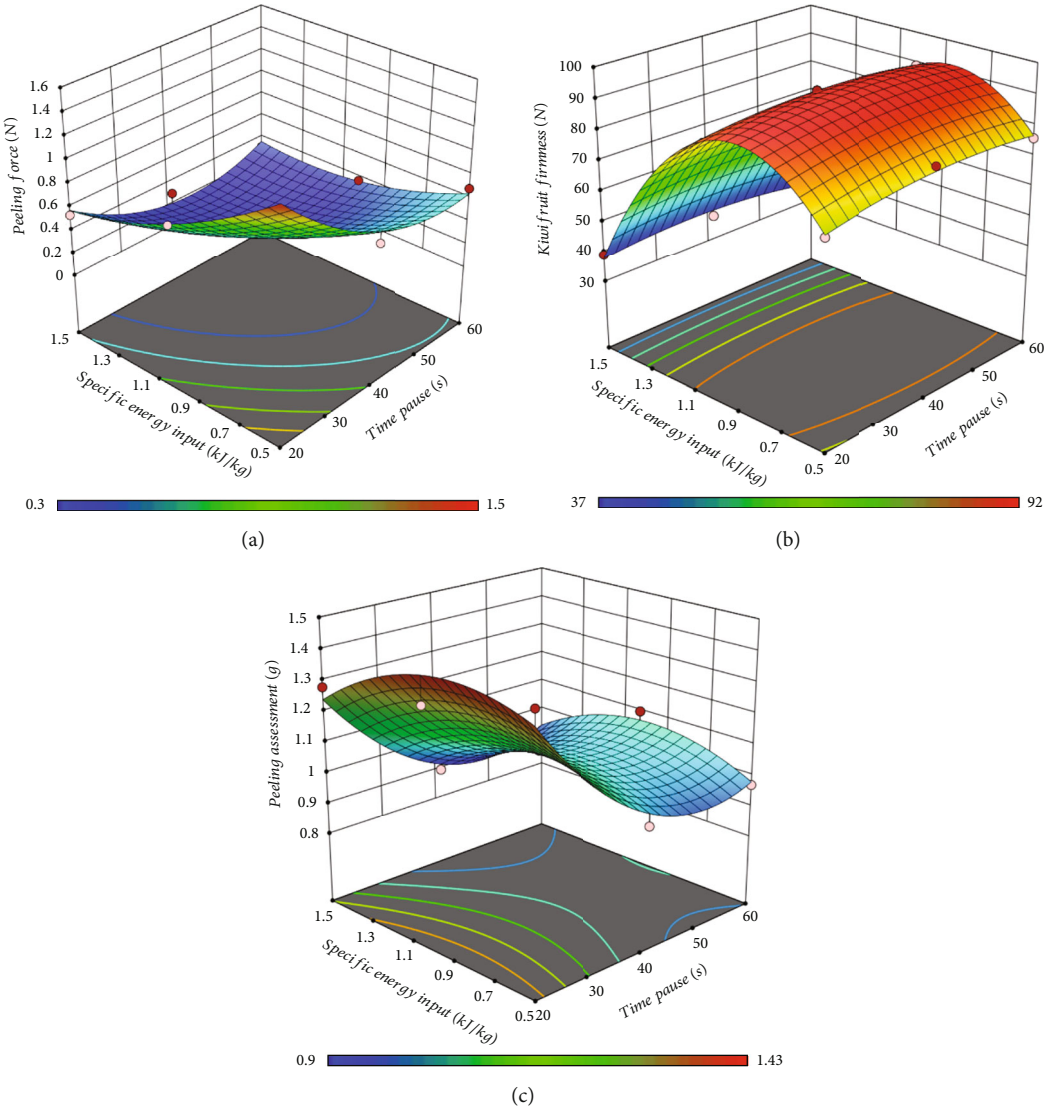


Figure 5: Response surface plots of specific energy and time pause after PEF treatment on peeling force (a), kiwifruit firmness (b), and peeling assessment (c).

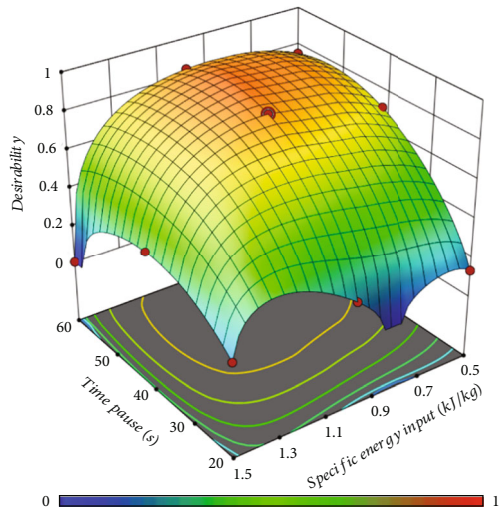


Figure 6: Response surface plots of the optimization task.

In the case of PEF pretreatment, both skin and bagasse showed higher greenness, higher yellowness, and lower brightness. The observed colour difference can be linked to the caramelization that occurred on the surface of PEF-pretreated kiwifruit. Furthermore, untreated and PEF-pretreated kiwifruits demonstrated no statistically significant differences for the a^* and the Brix values (Table 4). In general, the effect of PEF treatment on kiwifruit colour can be explained by the increase of membrane permeability which could allow better access of enzymes to their substrates, resulting in enzymatic browning reactions [38, 39]. The kiwi pigments could also undergo oxidation by thermal decomposition during the dehydration step [40].

The Brix values increased after the PEF pretreatment. In fruit extracts, °Brix is used to indicate the percentage of soluble solids and is one of the most important factors for grading the quality of extracts. Dissolved solids are mainly present in the vacuole of the kiwifruit cell, as it is also the case for phenolic compounds [41]. Therefore, similar

Table 3: Influence of PEF treatment on the pH and water activity of kiwi skin and powder, compared to the untreated control. The table displays the pH and water activity values ($n = 2$) with their respective standard deviation (SD).

	pH flour (pH ± SD)	pH extract (pH ± SD)	Water activity a_w ± SD
PEF skin	3.65 ± 0.037	4.84 ± 0.012	0.59 ± 0.004
Control skin	3.86 ± 0.036	4.97 ± 0.010	0.45 ± 0.010
PEF bagasse	3.48 ± 0.012	4.74 ± 0.056	0.37 ± 0.013*
Control bagasse	3.85 ± 0.036	4.77 ± 0.042	0.38 ± 0.010

*Significant difference compared to control ($P = 0.001$).

Table 4: Influence of PEF treatment on the $L^*a^*b^*$ values and Brix of PEF-treated kiwi compared to the untreated control. The table displays the values for three ($L^*a^*b^*$ values) and two (Brix values) biological replicates with three technical replicates each. SD: standard deviation.

	$L^*a^*b^*$ units L^* ± SD	a^* ± SD	b^* ± SD	Brix ± SD
PEF skin	89.16 ± 0.00*	−0.64 ± 0.01	14.05 ± 0.00*	25.20 ± 0.10
Control skin	90.70 ± 0.00	−1.01 ± 0.61	12.82 ± 0.00	24.57 ± 0.40
PEF bagasse	92.42 ± 0.07	-0.39 ± 0.00	13.60 ± 0.11*	26.33 ± 0.84
Control bagasse	92.72 ± 0.01	−1.05 ± 0.02	13.80 ± 0.06	25.23 ± 0.06

*Significant difference to control ($P \leq 0.001$).

principles for their release will apply and will be discussed together with the total polyphenol content (TPC) of the extract later in the text.

3.6. Phenolic Compounds. The influence of the PEF treatment on the total phenolic compounds (TPC) was analyzed in two biological replicates with two technical replicates each, and the results are shown in Figure 7. The peel of the kiwifruit exhibited the highest phenolic content. Compounds such as protocatechuic acid, chlorogenic acid, caffeic acid, rutin, *p*-hydroxybenzoic acid, and quercetin are known to be present in kiwifruit peel [5].

There was a tendency for the PEF-treated samples to show higher phenolic contents compared to the untreated samples. It was found that the TPC of kiwifruit fruits skin treated by PEF was 108.47 ± 0.76 mg/100 g ($P < .05$) in comparison to 100.32 ± 0.87 mg/100 g in the control sample. The effect of PEF pretreatment on the retention of TPC can be explained by higher extraction efficiency caused by electroporation of the cell membrane. Increased permeability could promote solvent penetration and consequently more extraction of phenolic compounds. In the case of skin TPC value, there was no significant difference observed between the control and the PEF-treated samples ($P < 0.05$). The obtained results were similar to those reported by other researchers. There may also be variation in TPC depending on the fruit maturity or horticultural practices [42, 43].

3.7. Antioxidant Capacity. In general, the skin of all kiwi varieties tends to have higher biological activity compared to the pulp [44, 45]. This may be due to the higher content of some molecules such as flavonoids [46].

The antioxidant properties of kiwi depend on the content of vitamins C and P in the fruit tissue [47]. The biological activity of vitamin C from kiwifruits is enhanced in the presence of vitamin P, the functional significance of which lies in the ability to regulate the permeability of the walls of blood vessels [48]. The results of the determination of the antioxidant capacity of kiwi skin and bagasse are shown in Figure 8.

As can be seen, the antioxidant capacity of the PEF-treated bagasse was significantly higher than that of the control bagasse. The antioxidant capacity in kiwifruit peel followed the same trend as the total phenolic content. Antioxidant activities have been directly linked to the presence of polyphenols, while flavonoids, such as quercetin, kaempferol, epicatechin, and hesperidin, were described to possess antibacterial and antiviral activities [49]. The high content of flavonoids in the skin has been described to exert more powerful antioxidant, antibacterial, and anticancer activities than the pulp [50]. As for the intensity of the PEF treatment, Mannozzi et al. [38] observed a significant increase, around 15.7%, in the antioxidant activity assessed by DPPH in strawberry tissues treated at 200 V/cm and 10 μs (total treatment time of 10 s and specific energy of 1.92 kJ/kg). For kiwifruits, lower intensities of PEF (100 V/cm, 0.96 kJ/kg) were found more beneficial for the retention of antioxidant compounds (7%).

The antioxidant capacity of the PEF-treated skin is significantly lower than that of the control skin. The changes in the cellular membranes may have induced a greater release of bounded antioxidant compounds, making them more accessible during the extraction step. Due to the water migration mechanism (Figure 3) and skin thickness, it might be concluded that PEF could preserve the AA in skin tissue. Similar results were reported by Tylewicz et al. [51], who investigated the application of PEF (2.8 kV/cm, 750 pulses) and OD (55°C, 60 min) before the drying of goji berry at 60°C.

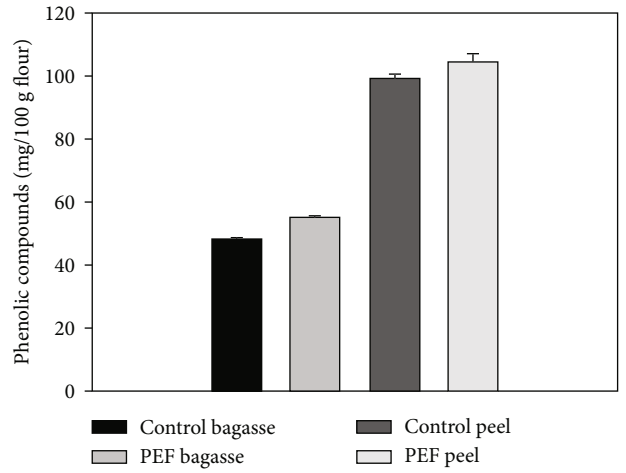


Figure 7: Influence of PEF treatment on phenolic compound (mg/100 g flour) of kiwi peel and bagasse, compared to the untreated control. Error bars represent the standard deviation of two biological replicates. No significant differences have been seen.

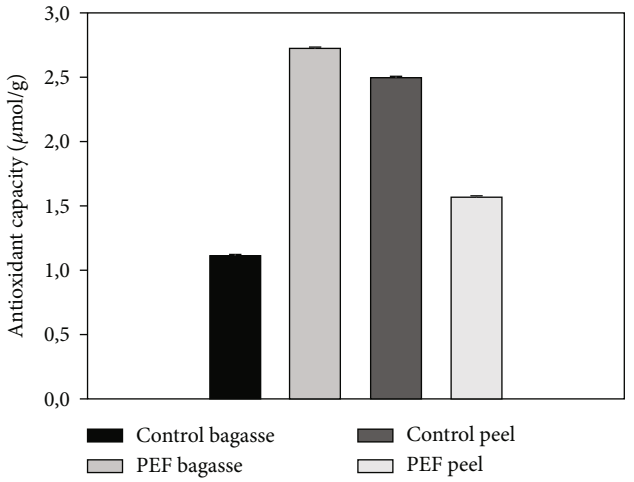


Figure 8: Influence of PEF treatment on the antioxidant capacity (μmol/g) of kiwi peel and bagasse, compared to the untreated control. Statistically significant differences have been observed between the bagasse and peel samples.

4. Conclusions

The results obtained in the current research showed that PEF pretreatment at the selected optimized conditions could be applied as a useful tool in the kiwifruit processing industry. The application of PEF could potentially minimize energy consumption, increase line productivity, and promote more effective valorization of kiwifruit waste. The optimization of specific energy and time pause parameters after treatment led to an improvement of peeling, as indicated by lower specific peeling force consumption and lower yield loss. Additionally, PEF was found to enhance the quality and effectiveness of the intracellular compounds extracted from kiwifruit peel and bagasse.

The improved peelability due to electropermeabilization can be explained by the migration of water from the mesocarp region under the kiwifruit skin. This led to a pressure difference across the kiwifruit skin, reducing the surface resistance and facilitating its removal. We demonstrated a clear potential for PEF to supplement existing mechanical peeling processes and help to reduce peel waste and lower the energy requirements. In the case of kiwifruit extracts, PEF pretreatment increased the quality attributes compared to the control.

Taking into consideration the low energy requirements of PEF (~1 kJ/kg of raw material), the technology could be an economically viable option for the kiwifruit processing industry. Moreover, PEF treatment could be applied to kiwifruit peel waste to obtain high phenolic compound yields. This valorization approach represents a natural alternative to the chemical synthesis of bioactive compounds that are used as ingredients in the food, cosmetic, or pharmaceutical fields. Overall, the application of PEF in kiwifruit processing offers an excellent example of how innovative, ecofriendly technologies can be used to reduce waste and promote a circular economy.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

This work has been presented as a poster at the 4th World Congress on Electroporation and Pulsed Electric Fields in Biology, Medicine, and Food & Environmental Technologies in Copenhagen (10/2022) [27].

Conflicts of 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.

Acknowledgments

The reported research was funded by the Russian Science Foundation (no. 21-79-00112, https://rscf.ru/en/project/21-79-00112/). The research was carried out using the equipment of the Research Center for Food and Chemical Technologies of KubSTU (CKP_3111) whose development is supported by the Ministry of Science and Higher Education of the Russian Federation (Agreement No. 075-15-2021-679).

References

[1] G. Khiralla and H. M. Ali, "Bioavailability and antioxidant potentials of fresh and pasteurized kiwi juice before and after in vitro gastrointestinal digestion," *Journal of Food Science and Technology*, vol. 57, no. 11, pp. 4277–4285, 2020.

[2] F. Liu, Z. Wu, X. Zhang et al., "Microbial community and metabolic function analysis of cigar tobacco leaves during fermentation," *Microbiology*, vol. 10, no. 2, article e1171, 2021.

[3] S. Wang, Y. Qiu, and F. Zhu, "Kiwifruit (*Actinidia* spp.): a review of chemical diversity and biological activities," *Food Chemistry*, vol. 350, article 128469, 2021.

[4] A. Siddique, N. Idrees, M. Kashif et al., "Antibacterial and antioxidant activity of kiwi fruit," *Biological and Clinical Sciences Research Journal*, vol. 2021, 2021.

[5] Y. Wang, L. Li, H. Liu et al., "Bioactive compounds and in vitro antioxidant activities of peel, flesh and seed powder of kiwi fruit," *International Journal of Food Science and Technology*, vol. 53, no. 9, pp. 2239–2245, 2018.

[6] W. Quan, Y. Tao, M. Lu et al., "Stability of the phenolic compounds and antioxidant capacity of five fruit (apple, orange, grape, pomelo and kiwi) juices during in vitro-simulated gastrointestinal digestion," *International Journal of Food Science and Technology*, vol. 53, no. 5, pp. 1131–1139, 2018.

[7] M. García-Quiroga, M. Nunes-Damaceno, M. Gómez-López et al., "Kiwifruit in syrup: consumer acceptance, purchase intention and influence of processing and storage time on physicochemical and sensory characteristics," *Food and Bioprocess Technology*, vol. 8, no. 11, pp. 2268–2278, 2015.

[8] U. Roobab, R. M. Aadil, G. M. Madni, and A. E.-D. Bekhit, "The impact of nonthermal technologies on the microbiological quality of juices: a review," *Comprehensive Reviews in Food Science and Food Safety*, vol. 17, no. 2, pp. 437–457, 2018.

[9] U. Roobab, M. A. Shabbir, A. W. Khan et al., "High-pressure treatments for better quality clean-label juices and beverages: overview and advances," *LWT*, vol. 149, article 111828, 2021.

[10] F. Salehi, "Physicochemical characteristics and rheological behaviour of some fruit juices and their concentrates," *Journal of Food Measurement and Characterization*, vol. 14, no. 5, pp. 2472–2488, 2020.

[11] M. Guldas, "Peeling and the physical and chemical properties of kiwi fruit," *Journal of Food Processing & Preservation*, vol. 27, no. 4, pp. 271–284, 2003.

[12] V. Sanz, L. López-Hortas, M. D. Torres, and H. Domínguez, "Trends in kiwifruit and byproducts valorization," *Trends in Food Science and Technology*, vol. 107, pp. 401–414, 2021.

[13] R. N. Arshad, Z. Abdul-Malek, U. Roobab et al., "Pulsed electric field: a potential alternative towards a sustainable food processing," *Trends in Food Science and Technology*, vol. 111, pp. 43–54, 2021.

[14] R. N. Arshad, Z. Abdul-Malek, U. Roobab et al., "Effective valorization of food wastes and by-products through pulsed electric field: a systematic review," *Journal of Food Process Engineering*, vol. 44, no. 3, article e13629, 2021.

[15] A. Lammerskitten, I. Shorstkii, O. Parniakov et al., "The effect of different methods of mango drying assisted by a pulsed electric field on chemical and physical properties," *Journal of Food Processing & Preservation*, vol. 44, no. 12, pp. 1–9, 2020.

[16] M. A. Kempkes, "Industrial pulsed electric field systems," in *Handbook of Electroporation*, D. Miklavcic, Ed., pp. 1–21, Springer International Publishing, Cham, 2017.

[17] M. D. Sosnin and I. A. Shorstkii, "Microplasma pretreatment of mango fruits during freeze drying with thermoelectric emission," *Food Processing: Techniques and Technology*, vol. 50, no. 4, pp. 681–689, 2020.

[18] D. Khudyakov, M. Sosnin, E. M. A. Munassar et al., "Pulsed electric field processing as an effective tomato peeling method," *Food Processing: Techniques and Technology*, vol. 1748, pp. 189–198, 2022.

[19] I. Shorstkii, M. Comiotto Alles, O. Parniakov et al., "Optimization of pulsed electric field assisted drying process of black soldier fly (*Hermetia illucens*) larvae," *Drying Technology*, vol. 40, no. 3, pp. 595–603, 2022.

[20] V. Andreou, G. Dimopoulos, E. Dermesonlouoglou, and P. Taoukis, "Application of pulsed electric fields to improve product yield and waste valorization in industrial tomato processing," *Journal of Food Engineering*, vol. 270, article 109778, 2020.

[21] R. Khodabakhshian, B. Emadi, M. Khojastehpour, and M. R. Golzarian, "Instrumental measurement of pomegranate texture during four maturity stages," *Journal of Texture Studies*, vol. 50, no. 5, pp. 410–415, 2019.

[22] X. Li, A. Zhang, G. G. Atungulu et al., "Effects of infrared radiation heating on peeling performance and quality attributes of clingstone peaches," *LWT - Food Science and Technology*, vol. 55, no. 1, pp. 34–42, 2014.

[23] X. Li, G. Bingol, T. H. McHugh, and G. Gregory Atungulu, "Feasibility study of using infrared radiation heating as a sustainable tomato peeling method," in *Presentation at the 2009 ASABE Annual International Meeting Sponsored by ASABE Grand Sierra Resort and Casino 0300*, Reno, Nevada, 2009.

[24] D. V. Batov, V. N. Kartsev, and S. N. Shtykov, "Preparation, heat capacity, and combustion characteristics of water-surfactant-halogenated hydrocarbon microemulsions suitable for combined fire-extinguishing means," *Russian Journal of Applied Chemistry*, vol. 85, no. 12, pp. 1905–1909, 2012.

[25] M. B. Soquetta, F. S. Stefanello, K. D. M. Huerta, S. S. Monteiro, C. S. Da Rosa, and N. N. Terra, "Characterization of physiochemical and microbiological properties, and bioactive compounds, of flour made from the skin and bagasse of kiwi fruit (*Actinidia deliciosa*)," *Food Chemistry*, vol. 199, pp. 471–478, 2016.

[26] R. Re, P. Nicoletta, P. Anna, P. Ananth, Y. Min, and R.-E. Catherine, "Antioxidant activity applying an improved ABTS radical cation decolorization assay," *Free Radical Biology & Medicine*, vol. 26, no. 9-10, pp. 1231–1237, 1999.

[27] I. Shorstkii, M. Sosnin, S. Smetana, S. Toepfl, O. Parniakov, and A. Wiktor, "Correlation of the cell disintegration index with Luikov's heat and mass transfer parameters for drying of pulsed electric field (PEF) pretreated plant materials," *Journal of Food Engineering*, vol. 316, article 110822, 2022.

[28] I. G. Medina-Meza and G. V. Barbosa-Cánovas, "Assisted extraction of bioactive compounds from plum and grape peels by ultrasonics and pulsed electric fields," *Journal of Food Engineering*, vol. 166, pp. 268–275, 2015.

[29] H. Li, P. Pidakala, D. Billing, and J. Burdon, "Kiwifruit firmness: measurement by penetrometer and non-destructive devices," *Postharvest Biology and Technology*, vol. 120, pp. 127–137, 2016.

[30] F. Guthrie, Y. Wang, N. Neeve, S. Y. Quek, K. Mohammadi, and S. Baroutian, "Recovery of phenolic antioxidants from green kiwifruit peel using subcritical water extraction," *Food and Bioproducts Processing*, vol. 122, pp. 136–144, 2020.

[31] E. Dermesonlouoglou, A. Chalkia, G. Dimopoulos, and P. Taoukis, "Combined effect of pulsed electric field and osmotic dehydration pre- treatments on mass transfer and quality of air dried goji berry," *Innovative Food Science and Emerging Technologies*, vol. 49, pp. 106–115, 2018.

[32] E. Dermesonlouoglou, I. Zachariou, V. Andreou, and P. S. Taoukis, "Quality assessment and shelf life modeling of pulsed

electric field pretreated osmodehydrofrozen kiwifruit slices," *International Journal of Food Studies*, vol. 7, pp. 34–51, 2018.

[33] M. V. Traffano-Schiffo, L. Laghi, M. Castro-Giraldez et al., "Osmotic dehydration of organic kiwifruit pre-treated by pulsed electric fields: internal transport and transformations analyzed by NMR," *Innovative Food Science and Emerging Technologies*, vol. 41, pp. 259–266, 2017.

[34] R. L. Monteiro, J. V. Link, G. Tribuzi, B. A. M. Carciofi, and J. B. Laurindo, "Effect of multi-flash drying and microwave vacuum drying on the microstructure and texture of pumpkin slices," *Lwt*, vol. 96, pp. 612–619, 2018.

[35] A. Lammerskitten, V. Mykhailyk, A. Wiktor et al., "Impact of pulsed electric fields on physical properties of freeze-dried apple tissue," *Innovative Food Science and Emerging Technologies*, vol. 57, article 102211, 2019.

[36] K. Rybak, K. Samborska, A. Jedlinska et al., "The impact of pulsed electric field pretreatment of bell pepper on the selected properties of spray dried juice," *Innovative Food Science and Emerging Technologies*, vol. 65, article 102446, 2020.

[37] T. P. Labuza and B. Altunakar, "Water activity prediction and moisture sorption isotherms," in *Water Activity in Foods*, pp. 161–205, John Wiley & Sons, Ltd, 2020.

[38] C. Mannozzi, U. Tylewicz, S. Tappi, M. D. Rosa, P. Rocculi, and S. Romani, "The influence of different pre-treatments on the quality and nutritional characteristics in dried undersized yellow kiwifruit," *Applied Sciences*, vol. 10, no. 23, p. 8432, 2020.

[39] U. Tylewicz, C. Mannozzi, J. M. Castagnini et al., "Application of PEF- and OD-assisted drying for kiwifruit waste valorisation," *Innovative Food Science and Emerging Technologies*, vol. 77, article 102952, 2022.

[40] D. Engin, "Effect of drying temperature on color and desorption characteristics of oyster mushroom," *Food Science and Technology*, vol. 40, no. 1, pp. 187–193, 2020.

[41] H. Jaeger, M. Schulz, P. Lu, and D. Knorr, "Adjustment of milling, mash electroporation and pressing for the development of a PEF assisted juice production in industrial scale," *Innovative Food Science and Emerging Technologies*, vol. 14, pp. 46–60, 2012.

[42] A. Wojdyło, P. Nowicka, J. Oszmiański, and T. Golis, "Phytochemical compounds and biological effects of Actinidia fruits," *Journal of Functional Foods*, vol. 30, pp. 194–202, 2017.

[43] H. Zhang, Q. Zhao, T. Lan et al., "Comparative analysis of physicochemical characteristics, nutritional and functional components and antioxidant capacity of fifteen kiwifruit (*Actinidia*) cultivars—comparative analysis of fifteen kiwifruit (*Actinidia*) cultivars," *Food*, vol. 9, no. 9, 2020.

[44] P. Latocha, B. Łata, and A. Stasiak, "Phenolics, ascorbate and the antioxidant potential of kiwiberry vs. common kiwifruit: the effect of cultivar and tissue type," *Journal of Functional Foods*, vol. 19, pp. 155–163, 2015.

[45] M. A. Skinner, K. Bentley-Hewitt, D. Rosendale, S. Naoko, and A. Pernthaner, "Effects of kiwifruit on innate and adaptive immunity and symptoms of upper respiratory tract infections," *Advances in Food and Nutrition Research*, vol. 68, pp. 301–320, 2013.

[46] E. Baranowska-Wójcik and D. Szwajgier, "Characteristics and pro-health properties of mini kiwi (*Actinidia arguta*)," *Horticulture, Environment and Biotechnology*, vol. 60, no. 2, pp. 217–225, 2019.

[47] D. Huang, W. Li, H. Shao, A. Gao, and X. Yang, "Colour, texture, microstructure and nutrient retention of kiwifruit slices subjected to combined air-impingement jet drying and freeze drying," *International Journal of Food Engineering*, vol. 13, 2017.

[48] A. C. Carr and M. C. M. Vissers, "Synthetic or food-derived vitamin C—are they equally bioavailable?," *Nutrients*, vol. 5, no. 11, pp. 4284–4304, 2013.

[49] Y. M. Kim, Y. S. Park, Y. K. Park et al., "Characterization of bioactive ligands with antioxidant properties of kiwifruit and persimmon cultivars using in vitro and in silico studies," *Applied Sciences*, vol. 10, no. 12, p. 4218, 2020.

[50] A. Alim, T. Li, T. Nisar et al., "Antioxidant, antimicrobial, and antiproliferative activity-based comparative study of peel and flesh polyphenols from Actinidia chinensis," *Nutrition Research*, vol. 63, 2019.

[51] U. Tylewicz, G. Oliveira, M. Alminger, L. Nohynek, M. Dalla Rosa, and S. Romani, "Antioxidant and antimicrobial properties of organic fruits subjected to PEF-assisted osmotic dehydration," *Innovative Food Science and Emerging Technologies*, vol. 62, article 102341, 2020.