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Exploring Varied (Green) Extraction Methods to Optimize Galia Melon Peel Antioxidant Potential

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Abstract: *Cucumis melo* L. (*C. melo*), commonly known as the melon, is a widely cultivated tropical fruit associated with nutritional benefits and bioactive properties. With global production reaching 40 million tons annually, the fruit processing industry generates significant waste, primarily peels, totaling 8 to 20 million tons yearly. These organic by-products are rich in bioactive compounds such as antioxidants, offering health benefits such as a reduced risk of cancer and cardiovascular diseases, as well as of diabetes and neurogenerative diseases, offering an opportunity for sustainable utilization. *C. melo* by-products have demonstrated various health benefits, including anti-inflammatory, analgesic, and antioxidant properties, attributed mainly to polyphenols. Recognizing the potential of melon waste, this study systematically explored different extraction methods, including stirring (ST), ultrasound (US), and pulsed electric field (PEF) methods, while considering factors such as extraction time, temperature, and solvent composition. The primary goal was to identify the most effective extraction procedures and optimal conditions for maximizing the yield of total polyphenols and antioxidant capacity (using the FRAP and DPPH methods) from *C. melo* peel by-products. According to the results, the optimum conditions include ST as the extraction method, an ethanolic solvent with a strength of 50%, a 150 min extraction duration, and an 80 °C extraction temperature. The maximum values of total polyphenols that can be observed are 3.75 mg gallic acid equivalents (GAE)/g of dry weight (dw) and 25.77 µmol ascorbic acid equivalents (AAE)/g dw and 34.44 µmol AAE/g dw from FRAP and DPPH antioxidant assays, respectively. The polyphenols identified were the following: gallic acid, neochlorogenic acid, catechin, chlorogenic acid, epicatechin, and kaempferol. By securing the maximum isolation of bioactive content and antioxidant activity, the research will contribute to sustainable waste management by reducing waste and developing value-added products.

Keywords: *Cucumis melo*; waste; extraction; ultrasonication; pulsed electric field; response surface methodology; antioxidant activity; polyphenols; principal component analysis; partial least squares

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1. Introduction

Cucumis melo L. (*C. melo*), commonly referred to as the melon, is a prominent tropical fruit [1] cultivated not only for its delightful taste [2] but also for its array of nutritional compounds (e.g., it is a rich source of vitamins such as vitamin C and E), as well as for its bioactive compounds like polyphenols [3]. Diets rich in polyphenols can prevent the development of certain cancers, cardiovascular diseases, diabetes, and neurodegenerative diseases [4] and achieve anti-inflammatory, analgesic, and antioxidant properties [5]. *C. melo*'s cultivation on a global scale yields approximately 40 million tons annually [6,7], underscoring its significance in the agricultural sector. However, this substantial production also gives rise to a consequential issue: the generation of a significant amount of waste, primarily comprising peels, which amounts to an estimated 8 to 20 million tons per year within the fruit processing industry [8]. Despite being considered waste, these

organic by-products possess a wealth of bioactive compounds [9,10] and strong antioxidant activity [11], presenting a promising avenue for sustainable utilization. The high levels of food waste generated by *C. melo*, in conjunction with the interest of the food industry in extracting bioactive compounds with beneficial properties from food by-products, can provide a solution to the global demand for novel, nutritious, and functional foods or applications such as food fortification products, enhancers, food preservatives, colorants, and natural antioxidants in food items like flour, biscuits, cakes, and bread [7,8,12].

Commercially, *C. melo* has various varieties with similar nutritional characteristics but different organoleptic properties. Specifically, there are evident differentiations among them regarding appearance, peel texture, the presence of coloration, and the absence of sutures during ripening, as well as variations in flesh, netting, shape, and pulp color [13]. Among the varieties are the Yellow melon (yellow peel and white flesh), Hybrid Pele-de-Sapo melon (light-green peel with dark-green spot and green fleshlight), Net/Honey Dew melon (yellowish peel and green flesh), Cantaloupe melon (most produced in the world, with orange flesh), Galia melon (green to yellow peel), and Charentais melon (green peel with dark-green ribs and orange flesh) [8,14,15]. According to a prior investigation conducted on the peel of the Cantapoule melon, no polyphenols were detected [16,17]. In addition, polyphenols were absent in the seeds of diverse varieties except the Maazoun melon, wherein a substantial [17,18] concentration of polyphenols, totaling 304.10 mg gallic acid equivalents (GAE)/100 g, was identified [9].

Galia is a muskmelon type of the F1 hybrid melon of *Cucumis melo* var. *reticulatus* and constitutes a climacteric fruit, with a storage duration of 2 weeks or less, even when maintained at low temperatures of around 8 °C [19]. In a previous study examining non-organic and organic Galia peels from Honduras, as well as organic peels from Mexico, significant quantities of phenolic and flavonoid compounds were found. Specifically, 3-hydroxybenzoic acid, chlorogenic acid, neochlorogenic acid, isovanillic acid, and luteolin-7-*O*-glucoside were detected while small or negligible quantities of apigenin-7-*O*-glucoside and kerstetrin-3-galactoside were also observed. Additionally, in the same study, extraction was conducted using simple manual agitation and supplemental mechanical stirring with a three-dimensional bi-mixer with freeze-dried powder from Galia melon peel. Extraction was carried out using methanol as a solvent at a ratio of 1:10 (*w/v*), yielding total polyphenols at 2.96 ± 0.12 mg GAE/g extract and an antioxidant capacity at 0.26 ± 0.008 mg ascorbic acid equivalent (AAE)/mL extract as per the results [20].

The extraction technique is a key factor for the maximum isolation of bioactive substances such as polyphenols [21]. Conventional extraction methods wherein a simple mechanism is used are being replaced by green and innovative extraction methods that enhance the efficiency of the extraction–isolation of bioactive compounds, using less extraction time and smaller quantities of solvents [21,22]. Typical such methods are ultrasound (US) [22] and pulsed electric field (PEF) methods [23]. Utilizing the potential of Galia melon waste, this study embarked on a systematic investigation into various extraction methods, including both the conventional stirring (ST) technique [24] as well as the utilization of two innovative and environmentally friendly extraction methods: US and PEF methods [22,25]. Integral to this exploration is the assessment of extraction parameters such as time, temperature, and solvent composition, aimed at identifying the most effective extraction processes and optimal conditions for maximizing the antioxidant capacity yield from Galia melon peel. By achieving the enhancement within the maximum isolation of bioactive content and antioxidant activity, this research endeavored to significantly contribute to sustainable waste management practices. The reduction in the amount of waste and simultaneous development of value-added products from Galia melon peel not only address environmental concerns but also promise to create economic opportunities in the fruit processing industry.

2. Materials and Methods

2.1. Chemicals and Reagents

All chemicals and reagents are presented in detail in the Supplementary Materials.

2.2. Galia Melon Collection and Extraction Procedure

Melons were purchased from a local grocery store in the Karditsa Region (Greece). The fruits purchased belonged to the Galia melon type and were fully ripe (weight: around ~2.5 kg; diameter size: 7.3 cm; hard and thick rind with bright yellow base color; covered with a rough, corky, brown net; strong sweet aroma; and sugar content: 10 °Brix, which were according to the maturity requirements characteristics of Galia melon [26]). The samples were transferred to the laboratory and thoroughly washed. The peel was carefully removed, cut into small pieces, and placed in a Biobase BK-FD10P (Jinan, China) lyophilizer. Moisture was removed for 24 h. The dried peels were pulverized to a fine powder. Finally, the dry powder was stored at −40 °C until use.

For the extraction procedure, 1 g of freeze-dried melon peel powder was placed in a screw-capped vial along with 20 mL of the extraction solvent (this ratio was established following preliminary experiments, and proved to be the most effective for maximum isolation of polyphenols). Regarding the extraction solvent, its composition (% percentage of ethanol) is detailed in Table 1. Detailed extraction parameters are provided in Table 1 and Figure 1. ST was conducted at 500 rpm, employing various temperatures and durations. Before the extraction phase, certain samples underwent additional green extraction techniques such as PEF method with a pulse period of 1 ms (frequency: 1 kHz), pulse duration of 10 μs, and electric field density of 1.0 kV/cm. This setup comprised a mode/arbitrary waveform generator (UPG100, ELV Elektronik AG, Leer, Germany), a digital oscilloscope (Rigol DS1052E, Beaverton, OR, USA), a high-voltage power generator (Leybold, LD Didactic GmbH, Huerth, Germany), and two custom stainless-steel chambers (Val-Electronic, Athens, Greece). Additionally, US was employed using an Elmasonic P machine 180 W (Elma Schmidbauer GmbH, Singen, Germany) with a set temperature of 30 °C operating at 37 kHz. Before any treatment, the dried material was hydrated by immersing it in the solvent for 10 min. Post-extraction, the mixture was centrifuged for 10 min at 4500 rpm, and only the supernatant was utilized for further analysis.

Table 1. The actual and coded levels of the independent variables were used to optimize the process.

Independent Variables	Code Units	Coded Variable Level				
		1	**2**	**3**	**4**	**5**
Technique	X_1	ST	PEF + ST	US + ST	PEF + US + ST	–
C (%, *v*/*v*)	X_2	0	25	50	75	100
t (min)	X_3	30	60	90	120	150
T (°C)	X_4	20	35	50	65	80

2.3. Response Surface Methodology (RSM) Optimization of Extraction and Experiment Design

All information regarding the use of Response Surface Methodology (RSM) to optimize the sample performance is presented in the Supplementary Materials.

2.4. Analyses of Extracts and HPLC-Based Analysis of the Various Polyphenolic Compounds

The detailed information concerning the analysis of the extracts [27–30], encompassing the total polyphenol content (TPC), antioxidant activity (assessed via the FRAP assay and the DPPH free radical scavenging assay), and the procedure for identifying and quantifying polyphenolic compounds, is provided in the Supplementary Materials.

2.5. Statistical Analysis

The statistical analysis that was applied is presented in the Supplementary Materials in detail.

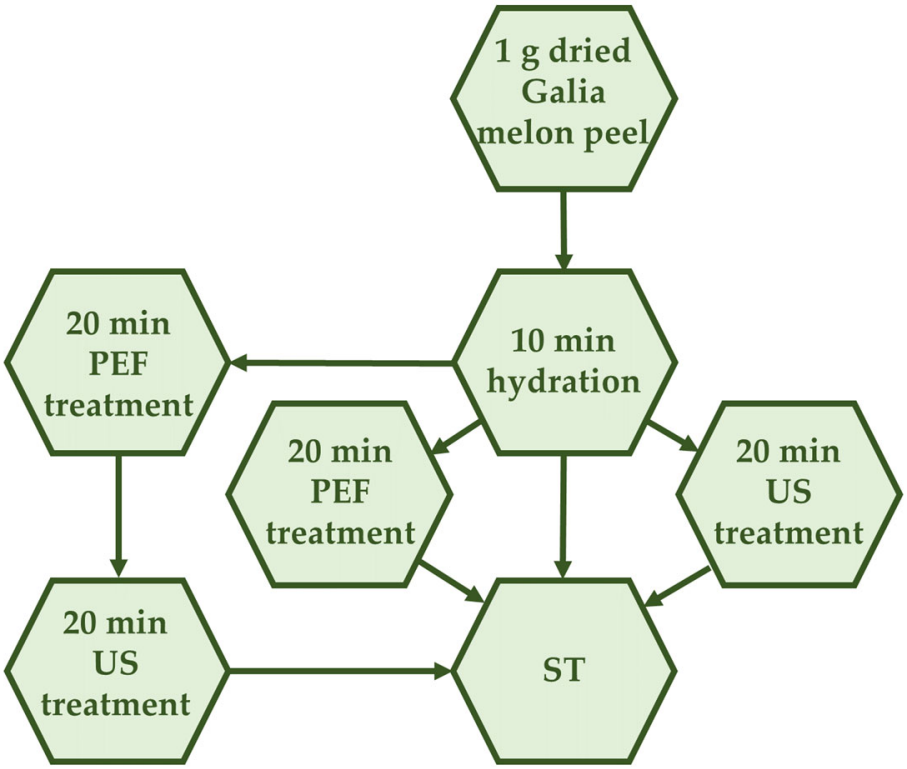

Figure 1. Graphical steps of the extraction process of Galia melon peel applying different techniques (ST: stirring, PEF: pulsed electric field, US: ultrasound).

3. Results and Discussion

The moisture lost during the lyophilization process was approximately 80%, which was an anticipated outcome considering that *C. melo* primarily comprises water [31].

3.1. Extraction Optimization

For securing the maximum quantity of polyphenolics from Galia melon peels, the response surface methodology (RSM) method was employed. Through this approach, the combination of all factors influencing the extraction, such as the extraction method, extraction time, extraction temperature, and solvent composition, was studied. Also, extraction methods including ST, US, PEF method, and their combinations were examined, with the extraction time of ST ranging from 15 to 150 min. Also, the temperature ranged from 20 to 80 °C, and the solvent consisted of water and ethanol in various proportions. Following preliminary experimental results, the optimal solid-to-solvent ratio was determined to be 1:20 (1 g dried Galia melon peels to 20 mL solvent).

Using the RSM approach, the impact of each factor was evaluated and adjusted to achieve maximum extraction efficiency. The measured responses for each extract are outlined in Table 2. Results indicate that design point 12 outperformed among the 20 samples, displaying optimal or near-optimal values across all measured responses. Neochlorogenic acid emerged as the primary phenolic compound in the extracts, with concentrations ranging from 5.12 to 769.61 μg/g dw, followed by catechin (6.13 to 318.80 μg/g dw) and chlorogenic acid (20.76 to 370.62 μg/g dw). Analysis was conducted using HPLC-DAD, with results summarized in Table 3, and a representative chromatogram is provided in Figure 2. Various phenolic compounds, such as gallic acid (0.13 to 8.85 μg/g dw), epicatechin (0.00 to 4.91 μg/g dw), and kaempferol (4.23 to 7.30 μg/g dw), were also detected.

Table 2. Experimental findings for the three independent variables under investigation and the dependent variable's responses.

Design Point	Independent Variables				Responses					
					TPC (mg GAE/g dw)		FRAP (μmol AAE/g dw)		DPPH (μmol AAE/g dw)	
	X_1	X_2	X_3	X_4	Actual	Predicted	Actual	Predicted	Actual	Predicted
1	3	1	3	4	2.39	2.38	14.66	14.82	15.83	15.81
2	3	2	1	3	2.81	2.86	17.08	17.51	20.35	20.61
3	2	3	4	3	3.28	3.19	23.28	23.27	24.71	23.61
4	2	4	5	4	2.87	2.92	22.62	22.37	24.57	27.13
5	3	5	4	2	1.40	1.35	11.29	10.90	12.42	12.59
6	4	1	4	5	2.12	2.16	14.06	14.11	3.38	4.04
7	4	2	3	1	2.81	2.79	16.96	16.91	7.97	8.77
8	1	3	3	2	3.56	3.65	23.45	23.91	23.90	26.13
9	1	4	4	1	3.30	3.28	17.53	17.52	34.72	33.86
10	1	5	1	4	1.80	1.75	13.46	13.26	5.68	5.12
11	1	1	2	3	3.07	3.12	18.54	18.44	23.25	24.70
12	1	2	5	5	3.72	3.67	23.25	23.18	39.85	38.40
13	4	3	2	4	3.17	3.08	17.93	17.36	16.74	14.25
14	3	4	2	5	2.19	2.16	15.87	15.87	20.02	22.04
15	2	5	3	5	1.59	1.67	14.59	14.94	22.27	21.36
16	2	1	1	1	2.73	2.66	26.02	25.86	34.31	33.97
17	2	2	2	2	2.96	2.97	23.78	23.58	26.58	23.96
18	3	3	5	1	2.53	2.58	16.60	16.68	20.06	20.06
19	4	4	1	2	2.53	2.60	20.18	20.40	17.16	18.28
20	4	5	5	3	1.55	1.54	12.65	12.92	2.90	2.01

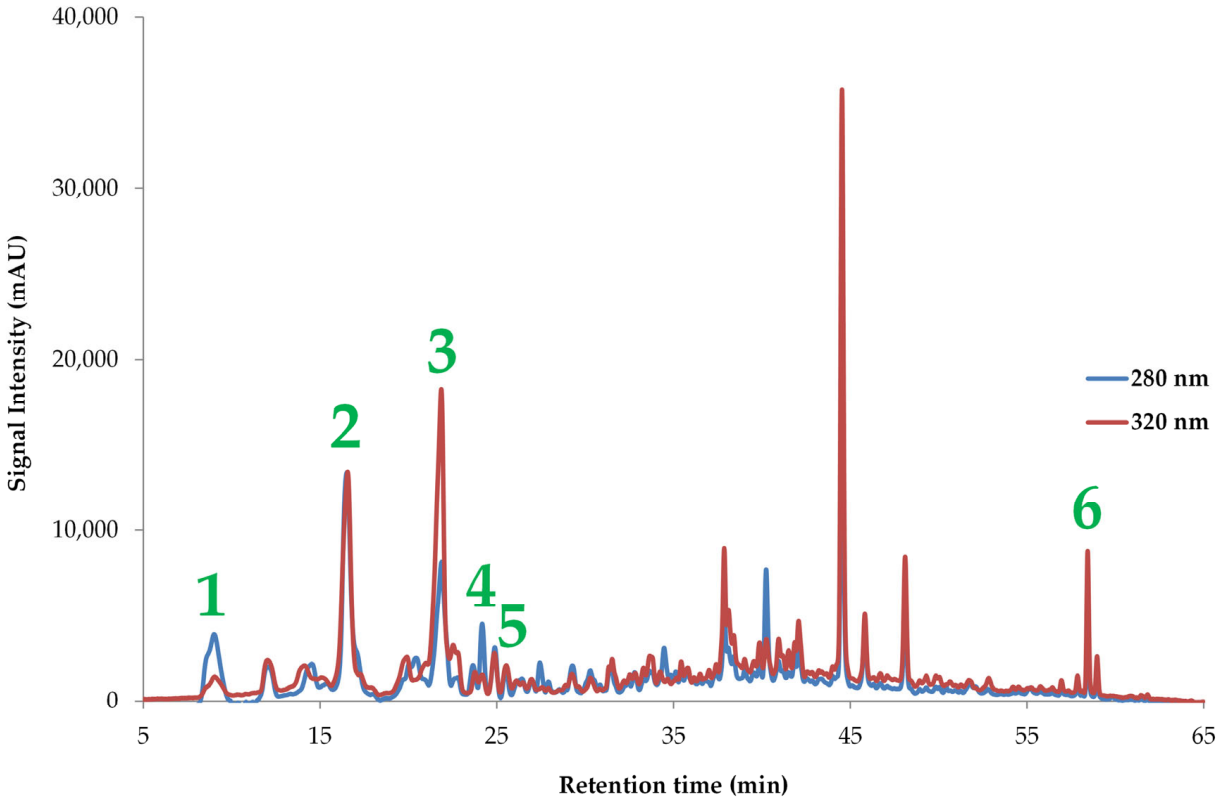

Figure 2. HPLC chromatogram at 280 and 320 nm of Galia melon peel optimal extract, demonstrating polyphenolic compounds that were identified. 1: Gallic acid; 2: neochlorogenic acid; 3: catechin; 4: chlorogenic acid; 5: epicatechin; 6: kaempferol.

The three most prevalent polyphenolic compounds identified were neochlorogenic acid, catechin, and chlorogenic acid, representing almost 85.76, 52.74, and 40.55% of the total identified polyphenolic compounds in the respective optimal extracts 12, 13, and 3 as illustrated in Table 3. Neochlorogenic acid stands out for its noteworthy anti-inflammatory and anticancer attributes [32], attainable by extracting the peel using a simple ST method, with an ethanol solvent concentration of 25% *w/w*, and subjecting it to high temperatures reaching 80 °C. Catechin was not detected in many *C. melo* varieties [33]. However, as evidenced in our case, the extraction technique has a major impact on the catechin content since its concentration could be increased by 98%, as can be seen in Table 3. This discovery holds significant implications, as food products abundant in catechin are often recommended for their therapeutic potential against chronic ailments like inflammatory bowel disease [34]. For the optimal extraction of catechin, preliminary treatment with the PEF method and US prior to ST is imperative, along with the utilization of an ethanol solvent concentration of 50%, as per the results outlined in Table 3. Similarly, in the case of chlorogenic acid, the utilization of the PEF method as a pretreatment, along with an ethanol solvent concentration of 50%, is crucial, given that they can enhance its content up to 94.40%. This result is noteworthy considering that according to a previous study, chlorogenic acid was not detected [35].

Table 3. Coded values of the four independent variables under investigation and the actual concentration of polyphenolic compounds, represented in μg/g dw.

Design Point	Independent Variables				Responses						
	X_1	X_2	X_3	X_4	GA	NCA	CA	CGA	ECA	KA	Total Identified
1	3	1	3	4	0.13	5.12	87.50	137.45	3.34	4.44	237.98
2	3	2	1	3	0.92	255.76	23.88	157.22	2.36	4.24	444.38
3	2	3	4	3	4.18	476.57	51.73	370.62	3.56	7.30	913.97
4	2	4	5	4	2.35	280.75	95.52	185.51	1.39	6.18	571.70
5	3	5	4	2	0.66	19.55	8.92	22.79	0.26	4.60	56.77
6	4	1	4	5	3.44	36.03	32.64	98.92	1.06	5.03	177.11
7	4	2	3	1	5.39	106.37	21.39	156.42	2.23	4.21	296.00
8	1	3	3	2	4.82	240.19	23.14	184.11	2.36	4.73	459.35
9	1	4	4	1	8.85	201.18	53.83	81.10	0.39	4.47	349.82
10	1	5	1	4	2.46	40.79	71.76	54.26	0.11	4.96	174.34
11	1	1	2	3	5.71	177.88	51.64	215.33	3.52	5.01	459.09
12	1	2	5	5	0.54	769.61	83.31	33.06	4.91	5.95	897.38
13	4	3	2	4	3.34	250.22	318.80	24.77	2.95	4.41	604.48
14	3	4	2	5	1.04	118.27	38.07	83.41	0.70	5.17	246.67
15	2	5	3	5	0.15	76.00	146.44	69.51	0.00	4.91	297.01
16	2	1	1	1	1.85	515.30	56.85	20.76	3.79	5.37	603.92
17	2	2	2	2	0.39	37.11	87.73	26.52	7.26	4.59	163.60
18	3	3	5	1	0.90	152.16	13.75	145.26	2.08	4.23	318.38
19	4	4	1	2	0.15	180.53	70.30	117.31	0.59	4.63	373.50
20	4	5	5	3	0.13	15.45	6.13	32.82	0.17	4.92	59.63

GA: Gallic acid; NCA: neochlorogenic acid; CA: catechin; CGA: chlorogenic acid; ECA: epicatechin; KA: kaempferol.

In Table 4, the statistical parameters, second-order polynomial equations (models), and coefficients (with values exceeding 0.92) for each model are offered, indicating a robust correlation between the established models and the data. Additionally, Figures S1–S3 depict plots comparing the actual response with the predicted response for each analyzed parameter, including desirability functions. Three-dimensional response plots are depicted in Figure 3 for a better comprehension of the TPC's dependence on the studied parameters. Moreover, three-dimensional response plots (Figures S4 and S5) are presented in the Supplementary Materials for the remaining parameters (FRAP and DPPH).

Table 4. Mathematical models created using RSM were used to optimize the extraction of Galia melon peel. The models contained only significant terms.

Responses	Second-Order Polynomial Equations (Models)	R^2	R^2 Adjusted	*p*-Value	Eq.
TPC	$Y = 3.09 - 0.93X_1 + 0.48X_2 + 0.44X_3 + 0.05X_4 + 0.2{X_1}^2 - 0.17{X_2}^2 + 0.01{X_3}^2 - 0.08{X_4}^2 - 0.003X_1X_2 - 0.16X_1X_3 + 0.06X_1X_4 - 0.003X_2X_3 + 0.09X_2X_4 - 0.002X_3X_4$	0.9932	0.9740	0.0002	(1)
FRAP	$Y = 35.69 - 2.71X_1 + 1.62X_2 + 0.46X_3 - 7.6X_4 - 0.44{X_1}^2 - 0.8{X_2}^2 + 0.24{X_3}^2 - 0.74{X_4}^2 + 0.61X_1X_2 - 0.45X_1X_3 + 1.17X_1X_4 - 1.16X_2X_3 + 1.38X_2X_4 + 1.27X_3X_4$	0.9962	0.9855	<0.0001	(2)
DPPH	$Y = 46.52 + 4.91X_1 - 9.79X_2 + 5.98X_3 - 13.71X_4 - 1.59{X_1}^2 + 0.2{X_2}^2 + 0.78{X_3}^2 + 1.01{X_4}^2 + 1.56X_1X_2 - 3.82X_1X_3 + 1.51X_1X_4 - 0.02X_2X_3 + 1.07X_2X_4 - 0.03X_3X_4$	0.9798	0.9231	0.0027	(3)

3.2. Analysis of the Extracts

3.2.1. TPC of the Extracts

In Table 2, the outcomes derived from all applied extraction protocols were summarized. Concerning TPC, the recorded values ranged between 1.40 and 3.72 mg GAE/g dw, indicating a considerable increase of 165.71%. Optimal results were observed via ST extraction at 80 °C for 150 min. This result is particularly interesting considering that many polyphenols are thermosensitive compounds, and extractions at temperatures above 80 °C often result in reduced yields [36,37]. This bespeaks the fact that the contained polyphenols are less thermosensitive. Notably, the peel of the Galia variety typically contains a TPC below 3 mg GAE/g [20]. Hence, following the outlined experimental conditions, an augmentation of TPC by up to 20.43% can be achieved. From the results, it occurred that none of the two other methods resulted in an increase in the TPC, probably due to extended processing times [38].

In Table 5, the responses of all measured parameters are presented, employing the optimal conditions obtained through the partial least squares (PLS) analysis. The ST method emerged as the most favorable for all analyses, along with an extended extraction time (150 min). Although, in previous studies, the use of green extraction methods favored the TPC in various fruits or fruits by-products [23,39,40], in terms of Galia melon by-products, even though high TPC values were recorded using US or PEF pretreatments, they did not mark the optimum values, according to Tables 2 and 5. Additionally, ethanol solvent was found to be the most ideal at a concentration of 50%, which is a reasonable outcome. In more detail, pure ethanol or aqueous ethanol as a solvent is suitable for extracting phenolic compounds and phenolic derivative antioxidant compounds from natural sources [41]. This can be attributed to the lower polarity of ethanol or intermediate polarity of aqueous ethanol compared to water, which can favor the extraction of less polar polyphenols. Moreover, ethanol is also capable of developing both hydrogen bonds as well as intermolecular interactions between hydroxyl groups and the aromatic groups of polyphenols, favoring their extraction [42]. Given the benefits of ethanol for extraction and its suitability for human consumption, as well as the fact that ethanol is a well-established solvent for extraction processes (more commonly employed compared to more recently developed solvents such as ionic liquids or deep eutectic mixtures), ethanol was chosen among various organic solvents [41]. In addition, ethanol can be recovered using rotary evaporators, allowing its reuse for further extractions. Comparing the results according to the PLS model with the experimental values (Table 6), it is evident that the experimental values aligned with the predicted ones.

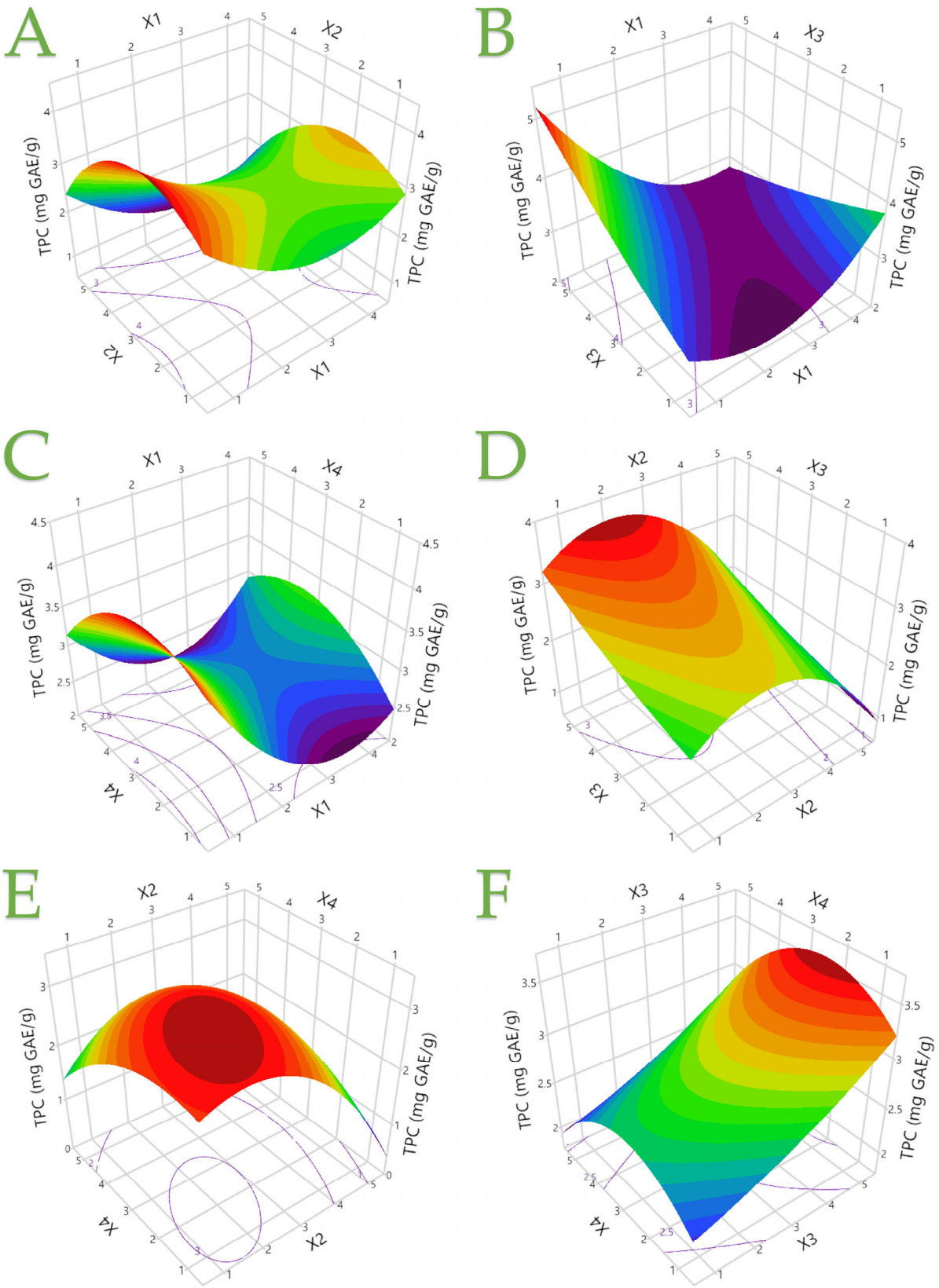

Figure 3. The optimal extraction of Galia melon peel extracts is shown in 3D graphs that show the impact of the process variables considered in the response (total polyphenol content—TPC, mg gallic acid equivalents (GAE)/g). Plot (**A**): covariation of X_1 and X_2; plot (**B**): covariation of X_1 and X_3; plot (**C**): covariation of X_1 and X_4; plot (**D**): covariation of X_2 and X_3; plot (**E**): covariation of X_2 and X_4; plot (**F**): covariation of X_3 and X_4.

Table 5. Maximum predicted responses and optimum extraction conditions for the dependent variables.

Responses	Optimal Conditions				
	Maximum Predicted Response	Technique (X_1)	C (%, v/v) (X_2)	t (min) (X_3)	T (°C) (X_4)
TPC (mg GAE/g dw)	4.0 ± 0.3	ST (1)	50 (3)	120 (4)	50 (3)
FRAP (μmol AAE/g dw)	26 ± 2	PEF + ST (2)	0 (1)	30 (1)	20 (1)
DPPH (μmol AAE/g dw)	38 ± 7	ST (1)	25 (2)	150 (5)	80 (5)

Table 6. Maximum desirability for all variables using the partial least squares (PLS) prediction profiler under the optimal extraction conditions (X_1:1, X_2:3, X_3:5, X_4:5).

Variables	PLS Model Values	Experimental Values
TPC (mg GAE/g dw)	3.75	3.6 ± 0.1
FRAP (μmol AAE/g dw)	25.77	26.4 ± 0.5
DPPH (μmol AAE/g dw)	37.44	36.8 ± 0.8

3.2.2. Polyphenolic Compounds of the Optimal Extract

Consuming foods rich in catechin is recommended for everyday diets due to their numerous health-promoting properties [43]. Catechin plays primary roles in removing reactive oxygen species, inhibiting free radical formation, and preventing lipid peroxidation [37]. Kaempferol has been shown to reduce the incidences of cerebrovascular diseases in humans [38] and prevents and reduces vascular inflammation, thrombus formation, and the oxidation of low-density lipoproteins [39]. As illustrated in Table 7, the primary polyphenolic component of the optimal extract is catechin. Under the optimal conditions, the isolation of catechin was significantly favored, unlike in the results presented in Table 3, where catechin accounted for a smaller proportion of the total polyphenolic compounds. Following the optimal conditions, catechin constitutes 40.24% of the total polyphenolic compounds, followed by kaempferol with 29.46% and neochlorogenic acid with 26.73%. Considering all the aforementioned data, it is evident that by applying the proposed extraction conditions, an extract can be produced that combines many polyphenols that exhibit beneficial properties suitable for daily human consumption.

Table 7. Polyphenolic compounds: analysis of optimal extract under optimal extraction conditions (X_1:1, X_2:3, X_3:5, X_4:5).

Polyphenolic Compounds	Optimal Extract (μg/g dw)
Gallic acid	6.0 ± 0.3
Neochlorogenic acid	314 ± 17
Catechin	472 ± 22
Chlorogenic acid	32 ± 2
Epicatechin	3.8 ± 0.2
Kaempferol	346 ± 12
Total identified	1173 ± 53

3.2.3. Antioxidant Properties of the Extracts

Two antioxidant assays, namely FRAP and DPPH, were conducted to obtain precise evaluations of antioxidant activities, given that each analysis cannot fully capture all antioxidants in a complex system. Tables 1, 2 and 5 indicate that the applied conditions affect each response differently. For example, regarding extraction time, the optimal duration for FRAP was 30 min (the minimum time) whereas for DPPH, it was 150 min (the maximum time). Similarly, the optimal temperatures differed, being 20 °C for FRAP and 80 °C for DPPH. Additionally, the best extraction method for FRAP requires an additional treatment (PEF) but utilizes 100% water as a solvent whereas for DPPH, the optimal conditions were achieved with simple ST and a 25% ethanol solvent.

The increase in antioxidant capacity using the FRAP method was from 11.29 to 26.02 μmol AAE/g dw, representing a 130.47% increase. Meanwhile, with the DPPH method, there was an increase of 1274.14% (from 2.9 to 39.85 μmol AAE/g dw). In a previous study, the peels of three different varieties of *C. melo* (Eminenza, SV7881, and Iperione) were examined using the FRAP method. The results for each variety were 2.45 ± 0.02, 3.79 ± 0.01, and 4.90 ± 0.02 μmol AAE/g, respectively [44]. These results were significantly lower compared to those achieved in our case. Additionally, the increased performance in scavenging free radicals observed with the DPPH method, assists in the reduction of oxidative stress, a harmful process that can adversely affect cellular membranes and other structures such as proteins, lipids, lipoproteins, and DNA [45–47]. These findings suggest that extracts from Galia melon peels could serve as antioxidants with numerous health benefits for humans.

3.3. Principal Component Analysis (PCA) and Multivariate Correlation Analysis (MCA)

In Figures 4 and 5, the correlation between various bioactive compounds and antioxidant capacity is illustrated in two different ways. Beginning with Figure 4, the first principal component (PC1) accounted for 48.4% of the variability and displayed a positive correlation with all variables, including polyphenolic compounds. Notably, among the extraction factors, X_1 showed the most substantial influence on increasing the studied bioactive compounds. As can be seen in Table 5, employing only the ST method yielded the maximum values. The choice of solvent appeared to have the second most significant impact, demonstrating a negative correlation.

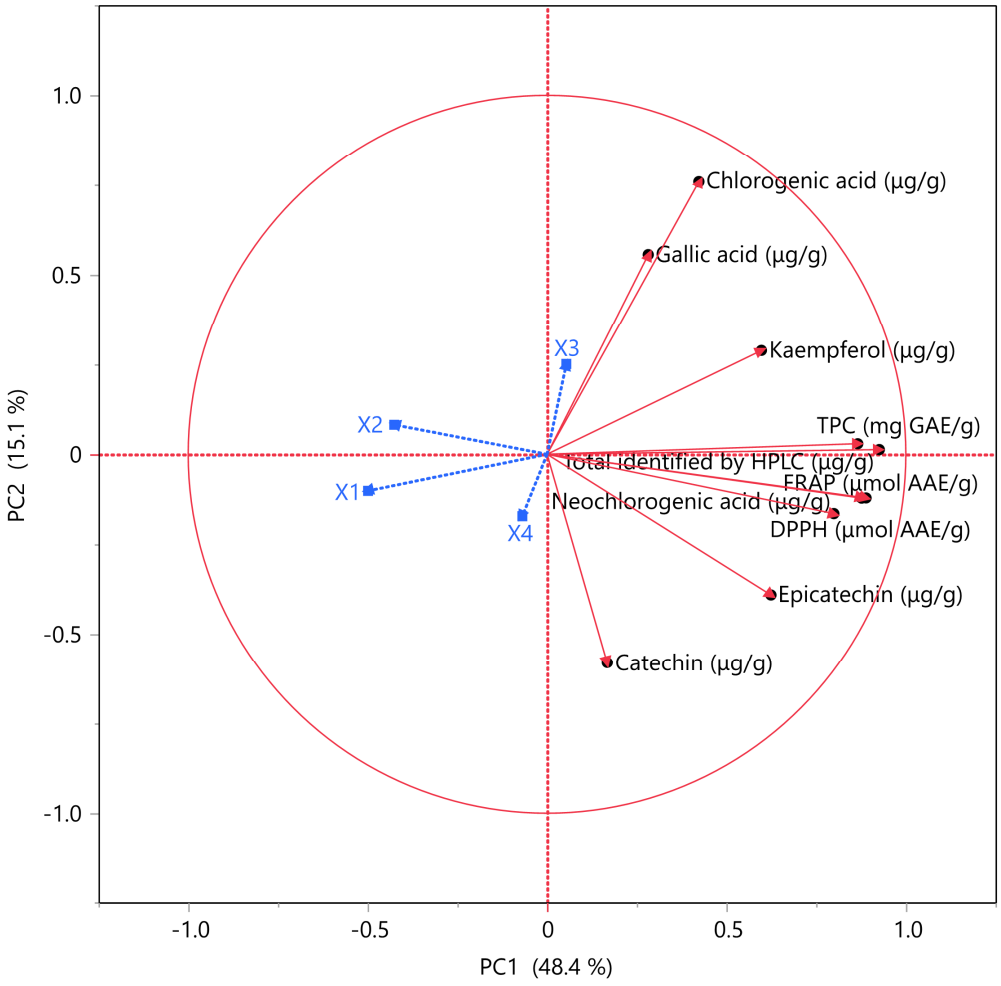

Figure 4. Principal component analysis (PCA) results for the measured variables. Each *X* variable is presented with a blue color.

Studying Figure 5 reveals the correlation between various bioactive compounds. One notable finding is the strong correlation of TPC not only with FRAP and DPPH responses but also with one of the primary polyphenolic compounds (neochlorogenic acid) and the total quantity of polyphenolic compounds. Furthermore, it is interesting to note that neochlorogenic acid and epicatechin exhibit a high degree of correlation with FRAP and DPPH responses. This suggests that these two polyphenolic compounds play a significant role in the antioxidant activity of the extracts from Galia melon peel. On the other hand, compounds like kaempferol and chlorogenic acid appear to contribute less to the antioxidant activity. Finally, there seems to be little to no correlation, or even negative correlation, among the other polyphenolic compounds, which could be attributed to their small quantities.

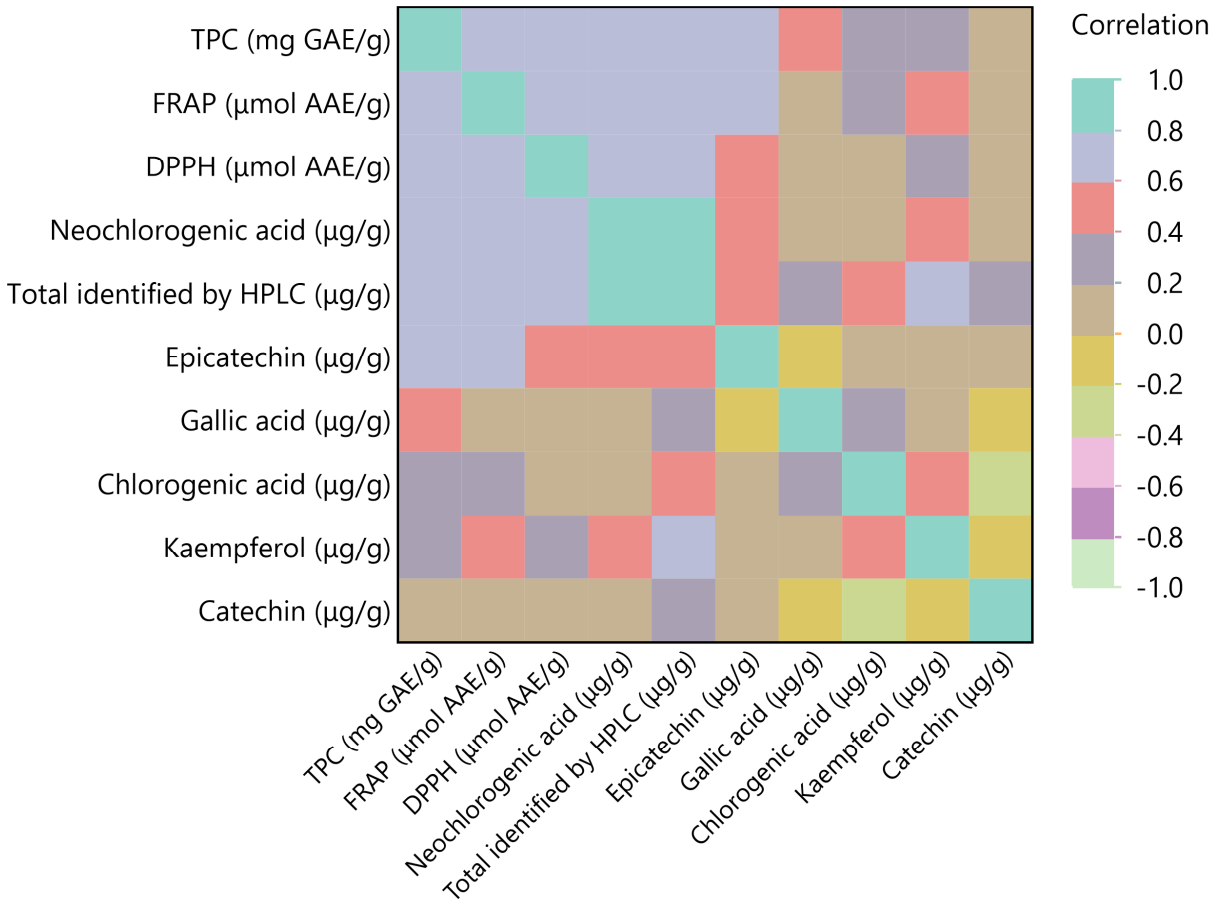

Figure 5. Multivariate correlation analysis (MCA) of measured variables.

3.4. Partial Least Squares (PLS) Analysis

The PLS analysis offers valuable insights for optimizing extraction conditions and helps in understanding the interplay of various factors affecting the yields of bioactive compounds. In this context, a PLS analysis, as depicted in Figure 6, was conducted to pinpoint the main factors among the investigated extraction variables (X_1, X_2, X_3, and X_4). Additionally, Figure 6 showcases the quantities of all potentially extractable bioactive compounds following the recommended extraction conditions derived from the PLS analysis. The desirability of the results is notably high, ranging from 0.9798 to 0.9962, with an optimum score of 1.0000. Upon reviewing Table 4, it becomes apparent that maximum values are ensured by employing the same parameters. Upon comparison of the values given by the PLS model with those obtained after experimental analysis, the correlation between them is found to be 0.9991 and they show no deviations with the p-value being 0.0005.

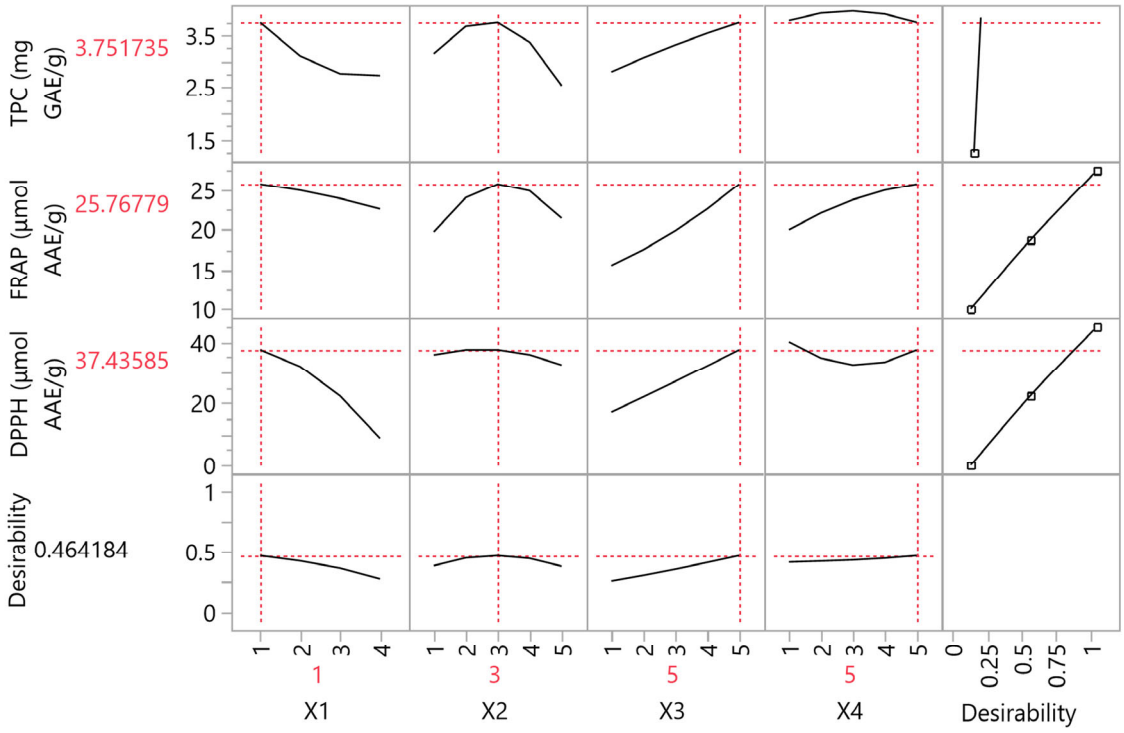

Figure 6. Partial least squares (PLS) prediction profiler of each variable and desirability function with extrapolation control for the optimization of Galia melon peel extracts.

4. Conclusions

In conclusion, this study underscored the potential of Galia melon peel by-products as rich sources of bioactive compounds, particularly polyphenols, with significant health benefits. By systematically exploring various extraction methods and optimizing conditions, the research identified optimal procedures (stirring (ST) extraction with a 50% ethanolic solvent at 150 min and 80 °C) for maximizing the yield of total polyphenols and antioxidant capacity. The results indicate that under these conditions, an enhanced TPC (enhanced by up to 20.43%) can be obtained, making an extract with significant health properties such as offering protection against the development of certain cancers, cardiovascular disease, diabetes, and neurodegenerative diseases. Although the TPC is lower compared to melon pulp, this is not a drawback since the pulp can be utilized alternatively in food product development whereas in our case, a waste material is valorized to produce added-value products. Although the PEF method and US are considered advanced extraction techniques that can promote the extraction of compounds, this is not always the case. This was also supported by our results, with the PEF method and US not favoring the extraction. This is not considered a drawback since the optimum extract can be obtained in a shorter time, with less energy consumption, and without the use of sophisticated equipment. All the above findings not only contribute to sustainable waste management by utilizing the fruit processing industry's by-products but also pave the way for the development of value-added products with enhanced nutritional and bioactive properties (which are expected to be retained upon proper storage) from an extract of the by-product of a beloved fruit. Moreover, these efforts align with the broader goals of promoting sustainability in food production and enhancing public health through the consumption of nutrient-rich and bioactive-rich products.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/separations11050135/s1, Supplementary Material File—Materials and Methods. Figure S1: Plot A displays the actual response versus the predicted response (Total polyphenol content—TPC, mg gallic acid equivalents (GAE)/g) for the optimization of Galia melon peel extracts using hydroethanolic solutions, different extraction techniques, and parameters, and plot

B displays the desirability function. Asterisks and colored values denote statistically significant values, while inset tables include statistics relevant to the evaluation of the resulting model; Figure S2: Plot A displays the actual response versus the predicted response (FRAP, μmol ascorbic acid equivalents (AAE)/g) for the optimization of Galia melon peel extracts using hydroethanolic solutions, different extraction techniques, and parameters, and plot B displays the desirability function. Asterisks and colored values denote statistically significant values, while inset tables include statistics relevant to the evaluation of the resulting model; Figure S3: Plot A displays the actual response versus the predicted response (DPPH, μmol ascorbic acid equivalents (AAE)/g) for the optimization of Galia melon peel extracts using hydroethanolic solutions, different extraction techniques, and parameters, and plot B displays the desirability function. Asterisks and colored values denote statistically significant values, while inset tables include statistics relevant to the evaluation of the resulting model; Figure S4: The optimal extraction of Galia melon peel extracts is shown in 3D graphs that show the impact of the process variables considered in the response (FRAP, μmol ascorbic acid equivalents (AAE)/g). Plot (A), covariation of X_1 and X_2; plot (B), covariation of X_1 and X_3; plot (C), covariation of X_1 and X_4; plot (D), covariation of X_2 and X_3; plot (E), covariation of X_2 and X_4; plot (F), covariation of X_3 and X_4; Figure S5: The optimal extraction of Galia melon peel extracts is shown in 3D graphs that show the impact of the process variables considered in the response (DPPH, μmol ascorbic acid equivalents (AAE)/g). Plot (A), covariation of X_1 and X_2; plot (B), covariation of X_1 and X_3; plot (C), covariation of X_1 and X_4; plot (D), covariation of X_2 and X_3; plot (E), covariation of X_2 and X_4; plot (F), covariation of X_3 and X_4.

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