Current **A**pplied **S**cience and **T**echnology e-ISSN: 2586-9396

Curr. Appl. Sci. Technol. 2027, Vol. 27 (No. 1), e0266317

Research article

Innovative Extraction of Phenolics from Longan Seeds through Pulsed Electric Fields

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Received: 13 February 2025, Revised: 3 October 2025, Accepted: 18 November 2025, Published: 24 March 2026

Abstract

Longan (*Dimocarpus longan* Lour.) seeds contain high levels of phenolic compounds with significant antioxidant properties. This study aimed to optimize the extraction of phenolics from longan seeds using pulsed electric field (PEF)-assisted extraction. A Box-Behnken design was employed to evaluate the effects of electric field intensity (kV/cm), extraction time (min), and solid-to-liquid ratio on total phenolic content (TPC). The optimal conditions were identified as 2 kV/cm, 9 min, and a 1:30 solid-to-liquid ratio, yielding 2.46±0.04 mg gallic acid equivalent (GAE)/g, a 14% increase compared to conventional maceration (2.16±0.08 mg GAE/g). Scanning electron microscopy (SEM) analysis revealed significant microstructural changes in the seed matrix after PEF treatment, leading to enhanced phenolic compound release. Statistical modeling confirmed the significance of extraction time and solvent ratio, with a strong model fit (R^2 = 0.9893). Compared to maceration, PEF-assisted extraction demonstrated superior efficiency in both extraction yield and phenolic recovery, reduced processing time, and minimized solvent usage, aligning with sustainable extraction practices. These findings highlight PEF as a promising non-thermal, energy-efficient technique for maximizing the recovery of bioactive compounds from agricultural byproducts.

Keywords: longan seeds; phenolic content; optimization; agricultural wastes; sustainability; pulsed electric field

1. Introduction

Phenolic compounds are a diverse group of secondary metabolites widely found in plants that are recognized for their potent antioxidant, anti-inflammatory, and antimicrobial properties (Liu et al., 2018; Shi et al., 2022; Zhang et al., 2022; Lazaridis et al., 2024).

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https://doi.org/10.55003/cast.2026.266317
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These bioactive compounds play a crucial role in human health by reducing the risk of chronic diseases such as cardiovascular disorders, cancer, and neurodegenerative conditions (Liu et al., 2018; Zhang et al., 2022). In recent years, the extraction of phenolic compounds from natural sources has gained significant attention due to their increasing demand in the food, pharmaceutical, and cosmetic industries (Liu et al., 2018; Shi et al., 2022; Zhang et al., 2022; Lazaridis et al., 2024). Among various plant-derived sources, longan (*Dimocarpus longan* Lour.) seeds have emerged as a promising reservoir of phenolic compounds, owing to their rich phytochemical composition and potent bioactivities (Tang et al., 2019; Tan et al., 2023). Longan is a tropical fruit widely cultivated in Southeast Asia and China that is known for its sweet and aromatic taste (Tang et al., 2019; Sai-Ut et al., 2023; Tan et al., 2023; Fikry et al., 2024). While the pulp is commonly consumed fresh or processed into various products, the seeds are often discarded as waste despite their high phenolic content (Tang et al., 2019; Tan et al., 2023). Studies have revealed that longan seeds contain abundant phenolic compounds, including gallic acid, corilagin, ellagic acid, and epicatechin, which exhibit remarkable antioxidant and therapeutic potential (Tang et al., 2019; Sai-Ut et al., 2023; Tan et al., 2023). To harness these valuable compounds, efficient and sustainable extraction techniques are essential to ensure maximum yield while maintaining bioactivity (Noore et al., 2022).

Traditional extraction methods, such as maceration, Soxhlet extraction, and heat-assisted extraction, have been widely employed for recovering phenolic compounds from plant materials (Jha & Sit, 2022; Bitwell et al., 2023). However, these methods have several limitations, including long extraction times, excessive use of organic solvents, high energy consumption, and the degradation of thermolabile compounds (Osorio-Tobón, 2020; Jha & Sit, 2022). These drawbacks not only reduce extraction efficiency but also pose environmental and economic concerns (Osorio-Tobón, 2020; Jha & Sit, 2022; Bitwell et al., 2023). To address these challenges, innovative extraction techniques have been explored to enhance the yield, purity, and functionality of phenolic compounds while minimizing environmental impact (Bitwell et al., 2023). Among these emerging techniques, pulsed electric field (PEF) extraction has gained significant attention as a non-thermal, energy-efficient method for recovering bioactive compounds (Fauster et al., 2018; Bocker & Silva, 2022).

PEF is an advanced, non-thermal processing technique that applies short, high-voltage electric pulses to plant tissues, inducing electroporation in cell membranes (Fauster et al., 2018; Naliyadhara et al., 2022). This process enhances mass transfer, facilitating the release of intracellular bioactive compounds, including phenolics, into the extraction medium (Niu et al., 2020; Naliyadhara et al., 2022). Compared to conventional methods, PEF offers several advantages, such as higher extraction efficiency, reduced processing time, lower solvent consumption, and better preservation of bioactive compounds (Liu et al., 2018; Niu et al., 2020). The effectiveness of PEF extraction depends on several critical factors, including electric field strength, pulse duration, frequency, and the type of solvent used (Carpentieri et al., 2023; Kronbauer et al., 2023). Optimization of these parameters is essential for the achievement of maximum extraction efficiency while maintaining the stability and bioactivity of phenolic compounds (Bazhal et al., 2003; Kronbauer et al., 2023). Recent studies have demonstrated that PEF-assisted extraction significantly improves the yield and antioxidant activity of phenolic compounds from various plant sources, including fruits (Carpentieri et al., 2023; Giancaterino & Jaeger, 2023; Ziaiifar et al., 2024), vegetables (Giancaterino & Jaeger, 2023; Ziaiifar et al., 2024), and medicinal herbs (Kronbauer et al., 2023; Chatzimitakos et al., 2024). However, limited research has been conducted on its application for extracting phenolic compounds from longan seeds.

The primary objective of this study is to investigate the potential of PEF-assisted extraction for enhancing the recovery of phenolic compounds from longan seeds. Specifically, it aims to evaluate the impact of key PEF parameters—electric field strength, pulse duration, and solid-to-liquid ratio—on extraction efficiency and optimize the conditions to achieve maximum phenolic recovery. Additionally, the study compares the efficiency of PEF-assisted extraction with conventional extraction techniques. The successful application of PEF technology for extracting phenolic compounds from longan seeds may facilitate its broader adoption in the processing of other plant-based bioactive compounds, providing valuable insights into the underlying mechanisms of PEF-assisted extraction and its role in enhancing the functionality and bioavailability of natural phenolic compounds.

2. Materials and Methods

2.1 Equipment used in this study

This study utilized specialized equipment to conduct the experiments efficiently. The PEF system used in this study is a prototype, as shown in Figure 1.

This portable machine integrates both PEF and ultrasonic systems. The process is operated by setting the parameters on a touchscreen pad, after which the 0.8 L chamber is inserted into either the PEF or ultrasound hub. The operation is initiated using the "start" command in Swift and stopped with the "stop" command in Swift.

2.2 Raw materials and preparations

The longan seeds used in this study were of the E-dor variety and were harvested during the growing season in July. They were obtained from Makhuea Chae Subdistrict Municipality, Mueang District, Lamphun Province. To remove contaminants, the seeds were washed with tap water before undergoing the drying process. Following the method of Narkprasom et al. (2018), the seeds were dried in a hot air oven at 70°C for three days. Once dried, they were coarsely ground using a grinder, stored in zip-lock bags, and kept in a desiccator to prevent moisture absorption for future use.

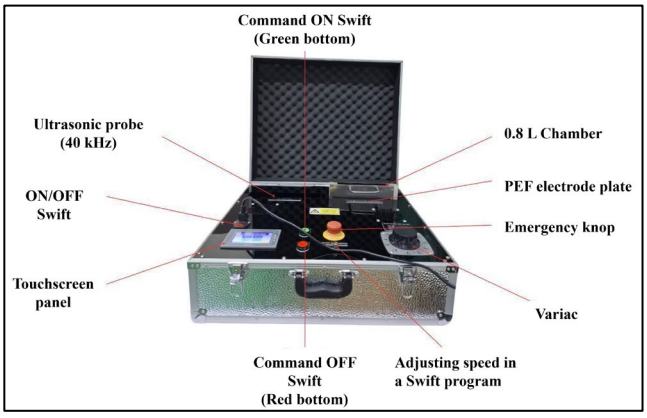


Figure 1. A prototype of a portable pulsed electric field (PEF) system integrated with an ultrasonic system

2.3 Experimental design

The experimental conditions for PEF were optimized using the Box-Behnken Design (BBD), a response surface methodology that allows for the assessment of interactions among multiple variables while minimizing the number of experimental trials (Porwal, 2022). The study focused on three key factors: intensity (kV/cm, A), extraction time (min, B), and solid-to-liquid ratio (C), each of which was tested at three levels. Following the Box-Behnken matrix (Table 1), a total of 14 experimental runs were performed.

The independent variable levels were set as follows: intensity at 1, 1.5, and 2 kV/cm; extraction time at 1, 5.5, and 10 min; and solid-to-liquid ratios of 1:10, 1:20, and 1:30. The experiments were carried out by weighing 1 g of longan seed powder and mixing it with a 50% ethanol solution (Keawsa-ard et al., 2020). The mixture was then subjected to extraction using the PEF system at a frequency of 1 kHz, following the intensity, duration, and solvent ratio conditions specified by the experimental design. After extraction, the mixture was filtered to separate the supernatant, which was then used to assess the total phenolic content (TPC).

Table 1. PEF-assisted extraction parameters for phenolic compounds from longan seeds

Run No.	Electric Field Intensity (kV/cm)	Extraction Time (min)	Solid to Liquid Ratio
1	1	1	1:20
2	2	1	1:20
3	1	10	1:20
4	2	10	1:20
5	1	5.5	1:10
6	2	5.5	1:10
7	1	5.5	1:30
8	2	5.5	1:30
9	1.5	1	1:10
10	1.5	10	1:10
11	1.5	1	1:30
12	1.5	10	1:30
13	1.5	5.5	1:20
14	1.5	5.5	1:20

2.3 Conventional extraction

Maceration was employed as the conventional extraction method. In this process, 1 g of longan seed powder was weighed and immersed in a 50% ethanol solution at a 1:30 ratio for 6 h at room temperature, following the procedure of Keawsa-ard et al. (2020) The extract was then filtered to separate the liquid, which was subsequently used to determine the TPC.

2.4 Determination of total phenolic content

The TPC of longan seed extracts was determined using the Folin–Ciocalteu colorimetric method (Salee et al., 2022). Briefly, 100 µL of Folin–Ciocalteu reagent (diluted 1:10) was mixed with 20 µL of the extract solution in a 96-well plate and kept in the dark for 4 min. Then, 80 µL of 7.5% (w/v) sodium carbonate was added, and the mixture was incubated

at 24±2°C for 2 h. The absorbance was measured at 760 nm using a microplate reader (DTX880, Beckman Coulter, Austria). TPC was quantified using a gallic acid standard curve (R^2 = 0.996), with results expressed as milligrams of gallic acid equivalent (GAE) per gram of extract.

2.5 Determination of extraction yield

The extraction yield of PEF using conventional extraction method was determined by measuring the mass of dried extract obtained relative to the initial dry weight of the raw material. After completion of the extraction process, the liquid extracts were filtered and concentrated under reduced pressure using a rotary evaporator at 40°C to remove the solvent. The concentrated extracts were then dried to a constant weight. Extraction yield was calculated according to the following equation (1):

$$\text{extraction yield } (\%) = \frac{\text{m}_{\text{extract}}}{\text{m}_{\text{raw material}}} \times 100 \quad (1)$$

where $m_{extract}$ is the mass of dried extract (g) and $m_{raw\ material}$ is the dry weight of the plant material used for extraction (g) (Kashaninejad et al., 2021). All experiments were conducted in triplicate, and results are expressed as mean±standard deviation.

2.6 Data analysis

All experiments were conducted in triplicate, with results reported as the mean±standard deviation. A second-order polynomial model (equation 2) was used to analyze the experimental data and determine the regression coefficients (*b*), using Design-Expert software version 13 (Stat-Ease Inc., Minneapolis, MN, USA).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 \quad (2)$$

Here, Y represents the response variable, while X_1, X_2, and X_3 are the independent variables or study factors. β_0 is a constant term, β_1, β_2, and β_3 are linear coefficients, β_{12}, β_{13}, and β_{23} are interaction coefficients, and β_{11}, β_{22}, and β_{33} are quadratic coefficients. The variations among the extracts were evaluated using one-way ANOVA at $p<0.05$ with the PSPP program (GNU, Boston, MA, USA). Group differences were further analyzed using an independent *t*-test at $p<0.05$, also utilizing the PSPP program.

3. Results and Discussion

3.1 Effect of PEF conditions on TPC of longan seeds

The TPC extracted from longan seeds using different PEF conditions are summarized in Table 2. The factors considered were electric field intensity (A), extraction time (B), and solid-to-liquid ratio (C). The results indicate that TPC values varied significantly based on the intensity (A), extraction time (B), and solid-to-liquid ratio (C). The highest TPC (2.33±0.05 mg GAE/g) was observed in experiment 12, where an intensity of 1.5 kV/cm, an extraction time of 10 min, and a solid-to-liquid ratio of 1:30 was applied. Conversely, the lowest TPC (1.06±0.06 mg GAE/g) was recorded in experiment 11, which utilized an intensity of 1.5 kV/cm, an extraction time of 5.5 min, and a solid-to-liquid ratio of 1:30.

The effect of intensity (A) on TPC extraction was evident, as higher intensity generally correlated with increase in TPC. For example, at a constant extraction time of 10 min and a solid-to-liquid ratio of 1:20, increasing the intensity from 1 kV/cm (experiment 3) to 2 kV/cm (experiment 4) resulted in an increase in TPC from 1.98±0.02 mg GAE/g to 2.26±0.09 mg GAE/g. This observation suggests that higher electric field intensities may enhance cell membrane permeability, facilitating the release of phenolic compounds (Angersbach et al., 2000).

Extraction time (B) also played a significant role in TPC yield. For instance, at an intensity of 1.5 kV/cm and a solid-to-liquid ratio of 1:10, increasing the extraction time from 1 min (experiment 9) to 10 min (experiment 10) led to an increase in TPC from 1.23±0.03 mg GAE/g to 1.64±0.01 mg GAE/g. This trend suggests prolonged exposure to PEF allows for a more efficient breakdown of cellular structures, leading to greater phenolic extraction (Chatzimitakos et al., 2023; Chatzimitakos et al., 2024). However, degradation or oxidation of phenolics may occur beyond an optimal duration, potentially reducing TPC values (Kronbauer et al., 2023).

The influence of the solid-to-liquid ratio (C) on TPC extraction was also noticeable. A higher solid-to-liquid ratio appeared to enhance TPC yield. For example, in experiments 10 and 12, where the solid-to-liquid ratio was increased from 1:10 to 1:30 while keeping other factors constant, the TPC value increased from 1.64±0.01 mg GAE/g to 2.33±0.05 mg GAE/g, respectively. This suggests that a higher solvent volume improves mass transfer efficiency, promoting the dissolution of phenolic compounds (Naliyadhara et al., 2022).

Table 2. Experimental values for the total phenolic compounds extracted from longan seeds using different PEF factors modeled by the Box-Behnken design

Run no.	Factors			TPC (mg GAE/g)[a]
	Electric Field Intensity (A; kV/cm)	Extraction Time (B; min)	Solid to Liquid Ratio (C)	
1	1	1	1:20	1.42±0.02^{g}
2	2	1	1:20	1.12±0.02^{hi}
3	1	10	1:20	1.98±0.02^{c}
4	2	10	1:20	2.26±0.09^{ab}
5	1	5.5	1:10	1.73±0.01^{ef}
6	2	5.5	1:10	1.78±0.04^{def}
7	1	5.5	1:30	1.86±0.20^{cde}
8	2	5.5	1:30	2.18±0.19^{b}
9	1.5	1	1:10	1.23±0.03^{h}
10	1.5	10	1:10	1.64±0.01^{f}
11	1.5	1	1:30	1.06±0.06^{i}
12	1.5	10	1:30	2.33±0.05^{a}
13	1.5	5.5	1:20	1.92±0.02^{cd}
14	1.5	5.5	1:20	1.83±0.02^{cde}

[a] The superscript letters denote statistically significant differences among samples (p<0.05), as analyzed using one-way ANOVA.

3.2 Statistical analysis and model fitting using RSM

The regression analysis of the second-order polynomial model for TPC extraction from longan seeds using PEF factors is presented in Table 3.

The model demonstrated a strong fit, as indicated by the high coefficient of determination (R^2 = 0.9893) and adjusted R^2 value (0.9651), suggesting that 96.51% of the variability in TPC extraction could be explained by the model. The adequacy of the model was further supported by an adequate precision value of 19.8816, which was well above the threshold of 4, indicating a desirable signal-to-noise ratio.

Among the individual factors, extraction time (B) exhibited the most significant effect on TPC, with a high sum of squares (1.43) and an extremely low *p*-value (<0.0001). This suggests that increasing the extraction duration significantly enhances TPC yield. The solid-to-liquid ratio (C) also played a critical role, showing a statistically significant impact (p = 0.0081), indicating that adjusting the ratio can influence the phenolic compound extraction. In contrast, intensity (A) had a weaker influence (p = 0.1738), implying that variations in electric field intensity alone may not substantially impact TPC extraction under the tested conditions.

In terms of interaction effects, BC (interaction between extraction time and solid-to-liquid ratio) was highly significant (p = 0.0047), demonstrating that the combined effect of these two factors played a crucial role in optimizing phenolic extraction. The interaction between AB (intensity and time) also showed significance (p = 0.0181), while AC (intensity and ratio) had a weaker effect (p = 0.1425). The quadratic term for B^2 (extraction time) was highly significant (p = 0.0042), suggesting a nonlinear relationship where increasing extraction time beyond a certain point may not proportionally enhance TPC yield. However, A^2 and C^2 were not significant, indicating a relatively linear influence of these parameters.

Table 3. Regression coefficients of the second-order polynomial model for TPC extraction from longan seeds using PEF factors

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	2.12	9	0.2357	40.90	0.0014	significant
A-Intensity	0.0157	1	0.0157	2.73	0.1738	
B-Time	1.43	1	1.43	247.56	< 0.0001	
C-Ratio	0.1376	1	0.1376	23.87	0.0081	
AB	0.0860	1	0.0860	14.93	0.0181	
AC	0.0191	1	0.0191	3.32	0.1425	
BC	0.1857	1	0.1857	32.23	0.0047	
A^2	0.0159	1	0.0159	2.75	0.1724	
B^2	0.1999	1	0.1999	34.69	0.0042	
C^2	0.0100	1	0.0100	1.74	0.2573	
Residual	0.0230	4	0.0058			
Lack of Fit	0.0190	3	0.0063	1.54	0.5202	not significant
Pure Error	0.0041	1	0.0041			
Cor Total	2.14	13				

Note: R^2 = 0.9893; Adjusted R^2 = 0.9651; C.V. % = 4.37; Adeq Precision = 19.8816

The model's residual error (0.0230) was minimal, reinforcing the model's reliability. The lack-of-fit test (p = 0.5202) was not significant, confirming that the model adequately describes the experimental data without unexplained variation (Brahimi et al., 2024).

These findings highlight that extraction time and solid-to-liquid ratio are the most influential factors in optimizing TPC extraction from longan seeds using PEF, while intensity has a comparatively lesser effect. Based on the multiple regression analysis, the final equation is presented below as equation 3.

$$\begin{aligned} TPC = {} & +2.48 - 1.39\ Intensity + 0.0361 Time - 0.012\ Ratio + 0.065\ Intensity \times Time + \\ & 0.014\ Intensity \times Ratio + 0.005\ Time \times Ratio + 0.28\ Intensity^2 - 0.012 Time^2 - 0.0006\ Ratio^2 \end{aligned} \quad (3)$$

In the polynomial equation, a negative coefficient represents a diminishing effect of the factor on the response, while a positive coefficient indicates an enhancing influence (Porwal, 2022). The regression equation derived from the BBD is strongly supported by the ANOVA results, as evidenced by the high coefficient of determination (R^2 = 0.9893) and the statistical significance of key model terms, indicating a robust correlation between the predicted and experimental TPC values. Then, the 3D surface plots illustrate the interactions between different independent variables: intensity (kV/cm), time (min), and ratio (Figure 2).

The response surface analysis highlights that extraction intensity and solvent ratio significantly influence TPC, while extraction time has a minor effect. Figure 2A illustrates the interaction between electric field intensity (A) and extraction time (B). TPC increases with higher intensity, indicating that a stronger electric field enhances phenolic compound extraction (Chatzimitakos et al., 2024; Ziaiifar et al., 2024). However, prolonged extraction time results in a slight decline in TPC, possibly due to the degradation or oxidation of phenolic compounds from extended exposure (Kronbauer et al., 2023).

Figure 2B presents the combined effects of pulsed intensity (A) and the solvent-to-solid ratio (C). A higher solvent ratio leads to increased TPC, suggesting improved mass transfer and solubilization of phenolics (Angersbach et al., 2000). Pulsed intensity also plays a crucial role, with higher values correlating to greater phenolic yield (Niu et al., 2020; Bocker & Silva, 2022).

Figure 2C depicts the influence of extraction time (B) and solvent ratio (C) on TPC. An increase in both factors positively impacts TPC up to a certain threshold, beyond which TPC slightly declines, likely due to saturation or degradation (Zhang et al., 2020). The curvature of the surface suggests an optimal range for these parameters, beyond which excessive time or dilution does not enhance extraction efficiency.

3.3 Model validation

The optimal conditions were determined by maximizing response desirability. The initially identified parameters included a pulsed intensity (A) of 1.92 kV/cm, an extraction time (B) of 8.92 min, and a raw material-to-50% ethanol ratio (C) of 1:28.80, with a predicted yield of 2.495 mg GAE/g. However, to enhance practical feasibility in production, the conditions were adjusted to a pulsed intensity of 2 kV/cm, an extraction time of 9.00 min, and a raw material-to-50% ethanol ratio of 1:30. Under these revised conditions, the experimental yield was 2.46±0.04 mg GAE/g (n = 3), closely matching the predicted value and confirming the accuracy and reliability of the RSM model.

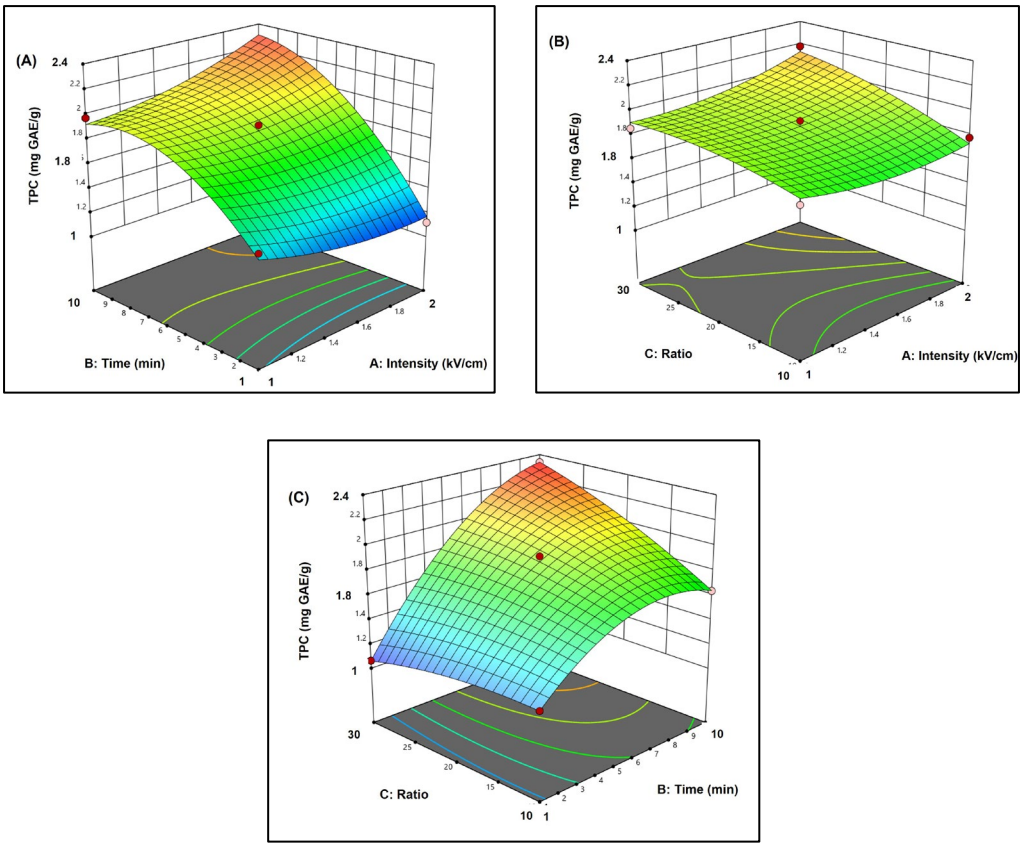


Figure 2. 3D surface plots depicting the predicted TPC of longan seed extracts based on variations in electric field intensity, extraction time, and the solid-to-liquid ratio. Specifically, Figure 2A showcases the interaction between intensity and time, Figure 2B illustrates the correlation between intensity and solid-to-liquid ratio, and Figure 2C represents the relationship between extraction time and solid-to-liquid ratio.

3.4 Comparison of PEF extraction with maceration

The TPC of longan seed extracts obtained using PEF-assisted extraction and maceration was compared to evaluate the efficiency of the optimized extraction method (Table 4).

Table 4. Comparison of the extraction yield and total phenolic compounds between the optimized PEF-assisted extraction condition and maceration.

Extraction Method	Extraction Yield (%)	TPC (mg GAE/g)
Maceration	10.13±2.56^{b}	2.16±0.08^{b}
PEF	18.21±3.24^{a}	2.46±0.04^{a}

Note: The different superscript letters in each column denote the significant differences between maceration and PEF-assisted extraction.

PEF-assisted extraction significantly enhanced both extraction yield and TPC content compared to conventional maceration. The extraction yield obtained with PEF (18.21±3.24%) was nearly two-fold higher than that of maceration (10.13±2.56%), indicating superior extraction efficiency under optimized PEF conditions. Similarly, the TPC of extracts obtained using PEF (2.46±0.04 mg GAE/g) was significantly higher than that obtained by maceration (2.16±0.08 mg GAE/g). These results demonstrate that PEF treatment improves the recovery of both total extract and phenolic compounds, highlighting its effectiveness as an advanced extraction technique compared to conventional maceration. PEF-assisted extraction enhances the release of phenolic compounds from the raw material (Liu et al., 2018; Niu et al., 2020; Lal et al., 2021).

The observed increase in both extraction yield and TPC using PEF-assisted extraction can be attributed to the electroporation effect, which disrupts cell membranes, facilitating improved mass transfer and solubilization of phenolic compounds (Angersbach et al., 2000; Carpentieri et al., 2023; Kronbauer et al., 2023). In contrast, maceration, a conventional extraction technique, relies primarily on diffusion, which is less efficient in breaking down cellular structures (Osorio-Tobón, 2020; Jha & Sit, 2022; Bitwell et al., 2023). The lower TPC yield in maceration suggests a limited extraction efficiency compared to the enhanced mechanism provided by PEF treatment (Fauster et al., 2018; Liu et al., 2018; Jha & Sit, 2022).

These findings highlight the potential of PEF-assisted extraction as a more effective technique for maximizing phenolic compound recovery, offering advantages in terms of extraction efficiency and yield.

3.5 Surface morphology of longan seed powder

The SEM images in Figure 3 illustrate the surface morphology of longan seed powder subjected to two different extraction methods: (A) maceration extraction and (B) optimized PEF (pulsed electric field) extraction, both at 1000× magnification.

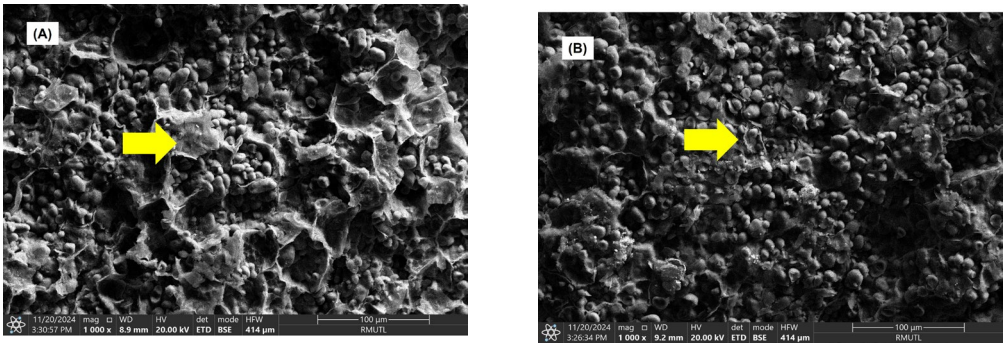


Figure 3. SEM images of longan seed powder: (A) maceration extraction and (B) optimized PEF extraction, visualized at 1000x magnification. Yellow arrows indicate changes on the surface of the longan seeds.

In Figure 3A, the maceration extraction process resulted in a rough and irregular surface structure, with noticeable porous and fragmented areas (indicated by the yellow arrow). The uneven surface suggests that maceration extraction causes significant

physical disruption but does not uniformly open the seed matrix, potentially limiting extraction efficiency (Osorio-Tobón, 2020; Jha & Sit, 2022; Bitwell et al., 2023).

In contrast, Figure 3B, which represents the optimized PEF extraction, displays a more homogeneous and granular structure with well-defined microstructures. The yellow arrow highlights smoother and more compact particle formations compared to maceration. This observation suggests that PEF treatment enhances the breakdown of cell walls, promoting a more controlled and efficient extraction process by increasing the surface area available for mass transfer (Liu et al., 2018; Koch et al., 2022; Giancaterino & Jaeger, 2023).

The SEM analysis confirms that PEF extraction significantly alters the microstructure of longan seed powder, making it a promising technique for improving extraction efficiency. The enhanced surface characteristics observed in Figure 3B support the potential benefits of PEF in optimizing bioactive compound recovery while preserving structural integrity. The improved disintegration of cellular structures in PEF-treated samples likely facilitates the release of bioactive compounds, leading to higher extraction yields and reduced processing times. This aligns with previous findings that PEF can enhance extraction efficiency by increasing membrane permeability while minimizing excessive physical degradation (Fauster et al., 2018; Liu et al., 2018; Mello et al., 2021; Koch et al., 2022; Giancaterino & Jaeger, 2023).

4. Conclusions

This study successfully demonstrated the efficiency of PEF-assisted extraction in enhancing the recovery of phenolic compounds from longan seeds. By optimizing key extraction parameters using the Box-Behnken design, the study identified optimal conditions that maximized total phenolic content while minimizing extraction time and solvent usage. Compared to conventional maceration, PEF-assisted extraction significantly increased both extraction yield and phenolic content, highlighting its potential as a sustainable and efficient technique for extracting bioactive compounds. The findings emphasize the importance of innovative extraction methods in valorizing agricultural byproducts, promoting sustainability in the food, pharmaceutical, and cosmetic industries. The improved extraction efficiency, combined with reduced processing time and energy consumption, makes PEF a promising alternative for industrial applications. Future research should explore the scalability of this method and its impact on the bioavailability and functionality of extracted phenolics. By integrating advanced extraction technologies, industries can enhance the utilization of natural antioxidants, aligning with circular economy principles and contributing to sustainable resource management.

5. Acknowledgements

The authors express their gratitude to the Innovation Center at Payap University, Chiang Mai, Thailand, for providing equipment support.

6. Authors' Contributions

Conceptualization, Sompong Paruchanon, Arthitaya Kawee-ai and Surapol Natakankitkul; methodology, Sompong Paruchanon, Arthitaya Kawee-ai and Surapol Natakankitkul; validation, Sompong Paruchanon, Arthitaya Kawee-ai and Surapol Natakankitkul; investigation, Sompong Paruchanon, Kriangsak Phramphun, Tanachai Pankasemsuk and

Arthitaya Kawee-ai and Surapol Natakankitkul; resources, Sompong Paruchanon and Supakiat Supasin; data curation, Sompong Paruchanon, Arthitaya Kawee-ai and Surapol Natakankitkul; writing—original draft preparation, Sompong Paruchanon, Arthitaya Kawee-ai and Surapol Natakankitkul; writing—review and editing, Sompong Paruchanon, Kriangsak Phramphun, Supakiat Supasin, Tanachai Pankasemsuk, Arthitaya Kawee-ai and Surapol Natakankitkul; visualization, Sompong Paruchanon and Arthitaya Kawee-ai; supervision, Supakiat Supasin, Arthitaya Kawee-ai and Surapol Natakankitkul; project administration, Arthitaya Kawee-ai and Surapol Natakankitkul.

7. Conflicts of Interest

No conflicts of interest are declared.

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