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Modeling the green extraction of bioactive compounds from Pilangkasa fruit (*Ardisia elliptica* Thunb) through empirical and machine learning approaches

Modelado de la extracción verde de compuestos bioactivos del fruto de Pilangkasa (*Ardisia elliptica* Thunb) mediante enfoques empíricos y de aprendizaje automático

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Abstract

Pilangkasa Fruit (*Ardisia elliptica* Thunb) contains the rich bioactive compounds, which still limited the study to utilization. This study aimed to investigate the effect of green extraction technique – ultrasoud-assisted extraction on the antioxidants recovery efficient and establish the kinetic extraction under different conditions. Five level of sonication amplitute (0, 25, 50, 75, 100%) were used for extraction at a time range from 0 to 90 minutes. The extraction yield (%), total phenolic compound (mg gallic acid equivalent per g, mgGAE/100 g), total anthocyanin content (mg/100 g) were determined. The experimental data was fitted with five empirical models to find the best fit model. The power of sonication greatly influenced the efficiency for recovering the phytochemical compounds in Pilangkasa fruit (*Ardisia elliptica* Thunb). The fast rate of extraction was found at the initial stage (after 30 min of extraction), then reached the equilibrium stage or slightly declined. Among the five empirical models, first-order model showed the best fit between the actual and predicted data. While, ANN model presented the fast and accurate prediction the extraction process. Based on the extraction rate constant from the first-order model, the level of around 50-75% of amplitute was considered as the appropriate condition for extraction polyphenol from Pilangkasa fruit with high yield of extraction, total polyphenol content, total anthocyanin content. These conditions could be further optimized and upscaled for used in food industry.

Keywords: artificial neural network, extraction, ultrasound, modeling, antioxidant.

Resumen

La fruta Pilangkasa (*Ardisia elliptica* Thunb) contiene compuestos bioactivos ricos, lo que aún limita el estudio para su utilización. Este estudio tuvo como objetivo investigar el efecto de la técnica de extracción verde – extracción asistida por ultrasonido en la eficiencia de recuperación de antioxidantes y establecer la cinética de extracción bajo diferentes condiciones. Se utilizaron cinco niveles de amplitud de sonicación (0, 25, 50, 75, 100%) para la extracción en un rango de tiempo de 0 a 90 minutos. El rendimiento de extracción (%), el contenido total de compuestos fenólicos (mg de ácido gálico equivalente por g, mgGAE/100 g) y el contenido total de antocianinas (mg/100 g) fueron determinados. Los datos experimentales se ajustaron a cinco modelos empíricos para encontrar el modelo que mejor se ajustara. La potencia de la sonicación influyó enormemente en la eficiencia para recuperar los compuestos fitoquímicos en la fruta Pilangkasa (Ardisia elliptica Thunb). La rápida tasa de extracción se encontró en la etapa inicial (después de 30 minutos de extracción), luego alcanzó la etapa de equilibrio o disminuyó ligeramente. Entre los cinco modelos empíricos, el modelo de primer orden mostró el mejor ajuste entre los datos reales y los predichos. Mientras tanto, el modelo ANN presentó una predicción rápida y precisa del proceso de extracción. Basado en la constante de tasa de extracción del modelo de primer orden, el nivel de alrededor del 50-75% de amplitud se consideró como la condición adecuada para la extracción de polifenoles de la fruta Pilangkasa con un alto rendimiento de extracción, contenido total de polifenoles y contenido total de antocianinas. Estas condiciones podrían ser optimizadas y ampliadas para su uso en la industria alimentaria.

Palabras clave: artificial neural network, extraction, ultrasound, modeling, antioxidant.

1   Introduction

Anthocyanins and polyphenols are significant natural substances owing to their potent antioxidant properties, which contribute to reducing oxidative stress and preventing degenerative diseases such as cardiovascular disorders, cancer, and diabetes (Khoo *et al*., 2017). Beyond their health-promoting effects, these compounds are increasingly valued in pharmaceutical formulations for their anti-inflammatory, antimicrobial, and neuroprotective activities (Lakshmikanthan *et al*., 2024). In the food industry, anthocyanins serve as natural pigments responsible for the red, purple, and blue hues of many fruits and vegetables, functioning as natural colorants, preservatives, and functional additives that enhance product stability and consumer acceptance (Le Loan *et al*., 2024). Consequently, the demand for anthocyanin- and polyphenol-rich extracts from plant materials continues to grow, driven by the need for bioactive, safe, and environmentally sustainable alternatives to synthetic additives and chemical preservatives.

Ardisia elliptica Thunb., referred to as Pilangkasa in Thailand, is a promising yet underutilized source of raw material. Pilangkasa fruits exhibit a rich purple hue and possess elevated concentrations of polyphenols, flavonoids, and anthocyanins, demonstrating significant antioxidant and antibacterial properties in *in vitro* research (Yukongphan *et al*., 2013). Compared to other well-known anthocyanin-rich species such as *Vaccinium myrtillus* (bilberry), *Rubus fruticosus* (blackberry), and *Hibiscus sabdariffa* (roselle), *A. elliptica* displays comparable or even higher total phenolic and anthocyanin contents on a fresh-weight basis (Yukongphan *et al*., 2013; Khoo *et al*., 2017; Le Loan *et al*., 2024). This positions it as a competitive natural source of antioxidants and health-promoting pigments. To effectively harness this potential, an optimal extraction technique is required to maximize the recovery of active compounds while preserving their structural integrity and minimizing the formation of undesirable degradation products.

Currently, green extraction techniques are receiving more attention owing to their safety, energy efficiency, and less environmental impact relative to conventional procedures that employ organic solvents and extended heating (Cannavacciuolo *et al*., 2024). Multiple studies indicate that a food-grade ethanol-water solvent (50–60%) can effectively extract polyphenols and anthocyanins from agricultural by-products, including grape pomace (Andishmand *et al*., 2023) and peach peel (Christaki *et al*., 2025). Selecting 60% food-grade ethanol as the solvent for extracting Pilangkasa fruit ensures the recovery of active components and its suitability for culinary and medicinal applications.

Besides solvent selection, extraction procedures are also crucial. Ultrasound-Assisted Extraction (UAE) is regarded as a promising eco-friendly technique that minimizes time and energy expenditure relative to conventional procedures (Loan, Vinh, & Tai, 2024). Ultrasonic waves generate cavitation, which is the creation and collapse of microbubbles in the solvent, producing shocks and microcurrents that compromise plant cell walls and facilitate the passage of solutes into the solvent (Bucur *et al*., 2023). The UAE facilitates low-temperature extraction, safeguarding thermosensitive chemicals such anthocyanins, while attaining enhanced recovery yields (Chemat *et al*., 2017). Nonetheless, the ultrasound intensity (amplitude) requires optimization: augmenting the intensity enhances the extraction rate, but surpassing the ideal threshold may lead to degradation of the active ingredient (Li *et al*., 2022).

Modeling extraction kinetics facilitates comprehension of fundamental mass-transfer mechanisms and improves the optimization of process parameters. Empirical models, such as the first-order, Peleg, and Elovich models, have been widely used to describe solute transport and release dynamics from plant matrices (Kayahan & Saloglu, 2020; Pavlić *et al*., 2023). The first-order model asserts that the extraction rate is exactly proportional to the difference between the equilibrium concentration and the solute concentration in the solvent, suggesting a diffusion-controlled process consistent with Fick's law (Kusuma & Mahfud, 2017). The Peleg model employs two constants to provide an empirical characterization of the extraction curve as one representing the initial extraction rate and the other denoting the equilibrium concentration (Rakshit, Srivastav, & Bhunia, 2020b). The Elovich model, first developed to clarify chemisorption kinetics, asserts that the extraction rate decreases exponentially with time, typically representing heterogeneous surfaces and complex adsorption–desorption processes (Rosa, Egido, & Márquez, 2019). By analyzing the variations in model parameters under varied operating settings, the researchers might be understand the influence of factors such as temperature, ultrasonic power, and solvent composition on the efficacy of mass transfer. This comparative modeling approach provides insights that enhance procedures to maximize bioactive molecule extraction while minimizing energy consumption and environmental impact (Bhadange, Carpenter, & Saharan, 2024). In recent years, machine learning techniques, particularly artificial neural networks (ANN), have been effectively utilized to forecast intricate extraction processes without predetermined kinetic equations (Bhagya Raj & Dash, 2022). Artificial Neural Networks (ANN) can more accurately characterize the non-linear relationships

between input variables (time, temperature, ultrasonic power) and output variables (extraction efficiency, polyphenol, and anthocyanin content) compared to empirical models (Loan, Vinh, & Tai, 2024).

This study aims to establish a sustainable and efficient extraction process for recovering bio-compounds from Pilangkasa fruit utilizing 60% food-grade ethanol and ultrasound-assisted extraction (UAE), while comparing the descriptive and predictive efficacy of empirical kinetic models with that of the artificial neural network (ANN) model. The study assessed the impact of extraction duration (0–90 min) and ultrasonic intensity (0%, 25%, 50%, 75%) on recovery efficiency, total polyphenol, and anthocyanin levels, consequently suggesting ideal conditions and prospective uses in the food and pharmaceutical sectors.

2 Materials and methods

2.1 Materials

Pilangkasa fruits (*Ardisia elliptica* Thunb.) were purchased from a local market in Samut Prakan Province, Thailand. The fruits were washed with distilled water and ground into a homogeneous puree. The obtained puree was stored in a dark, airtight container at 4 °C until further extraction was performed.

2.2 Extraction process

Sonication amplitude, defined as the extent of ultrasonic probe vibration that determines the intensity of acoustic cavitation, was varied at 0%, 25%, 50%, 75%, and 100% to evaluate its influence on extraction efficiency. The selected amplitude levels (were justified as representing a practical range that allows evaluation of both low- and high-intensity ultrasonic effects on extraction efficiency. An sonication bath (WUC-D10H, Wisd, Daihan Scientific, Korea) was used for operating the extraction process. Extraction treatment were performed a fruit puree–liquid ratio of 1:10 (w/v). The solvent used for extraction was 60% ethanol (food grade) (Loan *et al.*, 2023). The crude extracts were immediately centrifuged at 10,000 rpm for 1 min and filtered through filter paper under vacuum (V-700, Büchi, Switzerland) immediately after extraction. The extracts were collected in glass vials and stored at 4ºC until further analysis.

2.3 Extraction yield

Crude liquid extract was vacuum-evaporated and further dried to determine the total extraction yield. The results were expressed as the percentage of total extractable solids per 100 g of dry sample (%, w/w) as following equation:

$$\text{Extraction Yield (\%)} = \frac{\text{Weight of extract after solvent removal}}{\text{Dry weight of original sample}} \times 100 \quad (1)$$

2.4 Total phenolic content

The dried extract was dissolved again with methanol 80% before using for total phenolic content (TPC) analysis. The total phenolic content of extract was determined as the described method of Wanyo, Meeso and Siriamornpun (2014). Briefly, 300 μL of extract was mixed with 2.25 mL of Folin–Ciocalteu reagent (10%) and allowed to stand at room temperature for 5 min; 2.25 mL of sodium carbonate (60 g/L) solution was added to the mixture. After 90 min at room temperature, absorbance was measured at 725 nm using a spectrophotometer. Results were expressed as mg gallic acid equivalents in 1 g of dried sample (mg GAE/g) based on the standard curve: $y = 0.025x + 0.0632$ ($R^2 = 0.9957$), where: y is the absorbance value, and x is TPC (mg GAE/g).

2.5 Total anthocyanin content

The total anthocyanin content was assessed using the pH differential approach (Li *et al.*, 2022). Extracts were individually diluted with 0.025 M HCl–KCl buffer (pH 1) and 0.4 M CH$_3$COONa buffer (pH 4.5). The absorbance of the combination was quantified at 510 and 700 nm utilizing a UV-Vis spectrophotometer.

2.6 Kinetic modelling of the UAE of extraction yield, TPC, total anthocyanin of Pilangkasa fruit

Modeling the extraction kinetics is essential for understanding the mechanisms that govern mass transfer and solute diffusion during the process. Such modeling enables the prediction and optimization of extraction efficiency under various operating conditions and provides valuable information for the design of food and nutraceutical products with controlled composition and enhanced functional properties (Andishmand *et al.*, 2023; Lazar *et al.*, 2016; Loan *et al.*, 2025; Luangsakul *et al.*, 2025; Rakshit, Srivastav, & Bhunia, 2020a). In the present study, five mathematical models were used to fit the experimental data of TPC, extraction yield. The models were employed for the kinetic examination of extraction from plant materials (Kayahan & Saloglu, 2020; Kurtulbaş *et al.*, 2022; Pavlić *et al.*, 2023). The

equation and model name was listed as below:

First-order model : $C_t = C_{eq}(1 - e^{-kt})$ (2)

Peleg's model : $C_t = \dfrac{t}{(k_1 + k_2 t)}$ (3)

Modified Peleg model : $C_t = \dfrac{C_{eq}t}{k + t}$ (4)

Elovich's model : $C_t = E \ln(t) + a$ (5)

Power-law model : $C_t = Bt^n$ (6)

where: C_t is extraction yield/TPC/total anthocyanin at time (t); C_{eq} is theoretical equilibrium point; k, k_1, k_2, E, a, B, n are model constants.

The artificial neural network (ANN) analysis was performed using MATLAB_R2023b. A feedforward multilayer perceptron (MLP) was applied to model the relationship between ultrasonic power and extraction time (inputs) and extraction yield, the concentrations of polyphenols and anthocyanins (outputs). Data were normalized between 0 and 1 and divided into training (70%), validation (15%), and testing (15%) sets. The network was trained using the Levenberg–Marquardt backpropagation algorithm with activation in hidden layers (10 nodes) and a linear output function. Model accuracy was evaluated through coefficient determination (R) and MSE values.

2.7 Data analysis

STATGRAPHICS Centurion XV.I was used for nonlinear regression analysis. The agreement between the experimental data and the models were assessed by using mean squared error (MSE) and the correlation coefficient (R2). A low MSE and a high R2 value denote good fit (Dong *et al*., 2014). MATLAB v.2023b and the Levenberg-Marquardt (LM) training routines were used to train the model.

3 Results and discussion

3.1 Effect of sonication power on the extraction yield and empirical model kinetics

The experimental findings indicated that ultrasonic power significantly influenced the extraction efficiency from Pilangkasa fruit (*Ardisia elliptica* Thunb). Notably, elevating the ultrasonic intensity from 0% (absence of ultrasound) to 75% resulted in a substantial increase in the quantity of extraction yield (Figure 1). The extraction efficiency increased rapidly within the first 15–20 minutes for all ultrasonic amplitudes, reaching a near-equilibrium value afterward. The highest measured efficiency (18.47%) was obtained at 50% amplitude after 75

minutes, indicating that this power level provided the most favorable balance between cavitation intensity and solvent penetration. In comparison, efficiencies at 25%, 75%, and 100% amplitudes were slightly lower, ranging between 18.32% and 18.38%, while the lowest efficiency (18.08%) was recorded at 0% amplitude, corresponding to extraction without ultrasonic assistance. This trend suggests that moderate ultrasonic power enhances mass transfer by disrupting the cellular matrix and facilitating solute diffusion, whereas excessively high amplitude (100%) may cause structural degradation or localized overheating, slightly reducing extraction efficiency (Liu *et al*., 2022). Therefore, the results confirm that ultrasound application significantly accelerates the extraction process, with 50% amplitude yielding the most effective operational conditions. The enhancement in efficiency with elevated ultrasonic power is elucidated by the phenomenon of cavitation effect. Ultrasonic waves generate microbubbles in the solution, which subsequently collapse, producing microcurrents and shocks that significantly disrupt the cellular wall structure, thereby liberating a greater quantity of solutes into the solvent (Liu *et al*., 2022). During the initial phase (approximately 0–30 minutes), the extraction process occurred rapidly, resulting in the swift recovery of most of the solute before reaching the point of saturation thereafter. Nevertheless, when ultrasonic power reached excessive levels (100%), pronounced cavitation effects could induce localized overheating and partial degradation of the extract's molecular structure or generate turbulence that diminishes contact efficiency, resulting in a marginal reduction in actual yield relative to the optimal level. Our findings align with those of Luangsakul *et al*. (2025), who reported in their investigation of ultrasound-assisted extraction of polyphenols from *Gnaphalium affine* D. Don, identified an optimal power level for the extraction rate, beyond which the rate constant reduced.

The process kinetics were characterized by correlating the acquired data using various empirical models, including first-order, Peleg, Modified Peleg, Elovich, and Power-law models (Table 1).
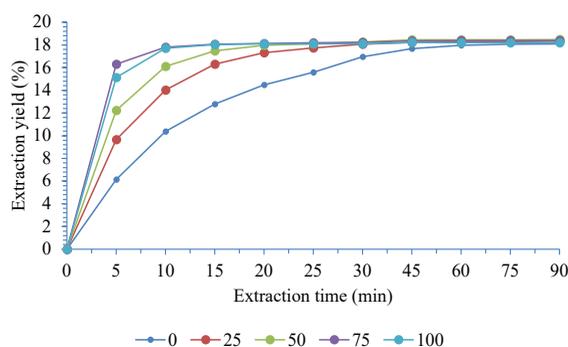

Figure 1. Effect of sonication conditions on the extraction yield of Pilangkasa fruit.

Table 1. Empirical model kinetic development for prediction the effect of sonication conditions on the extraction yield of Pilangkasa fruit.

Model	Ultrasound amplitude (%)	Model constants		R^2	MSE
$C_t = C_{eq}(1 - e^{-kt})$	0	k = 0.1823	C_{eq} = 0.0816	99.92	<0.0001
	25	k = 0.1828	C_{eq} = 0.1478	99.99	<0.0001
	50	k = 0.1834	C_{eq} = 0.2153	99.95	<0.0001
	75	k = 0.1824	C_{eq} = 0.4437	99.95	<0.0001
	100	k = 0.1815	C_{eq} = 0.3599	99.99	<0.0001
	Mean			*99.96*	*<0.0001*
$C_t = \dfrac{C_{eq}t}{k+t}$	0	k = 10.5901	C_{eq} = 0.2176	99.20	<0.0001
	25	k = 4.4651	C_{eq} = 0.2025	98.89	<0.0001
	50	k = 2.5255	C_{eq} = 0.1965	99.33	<0.0001
	75	k = 0.6492	C_{eq} = 0.1866	99.94	<0.0001
	100	k = 0.9702	C_{eq} = 0.1873	99.61	<0.0001
	Mean			*99.39*	*<0.0001*
$C_t = E \ln(t) + a$	0	E = 0.0465	a = -0.0014	94.59	<0.0001
	25	E = 0.0302	a = 0.0692	81.48	0.0002
	50	E = 0.0202	a = 0.1089	75.06	0.0001
	75	E = 0.0064	a = 0.1597	72.56	<0.0001
	100	E = 0.0086	a = 0.1501	58.69	<0.0001
	Mean			*76.48*	*<0.0001*
$C_t = Bt^n$	0	B = 0.0534	n = 0.3088	94.93	0.0002
	25	B = 0.0940	n = 0.1745	94.67	0.0002
	50	B = 0.1206	n = 0.1126	96.79	0.0001
	75	B = 0.1609	n = 0.0351	99.66	<0.0001
	100	B = 0.1525	n = 0.0477	98.83	<0.0001
	Mean			*96.98*	*0.001*
$C_t = \dfrac{t}{(k_1 + k_2 t)}$	0	k_1 = 48.6803	k_2 = 4.5966	99.20	<0.0001
	25	k_1 = 22.0507	k_2 = 4.9378	98.89	<0.0001
	50	k_1 = 12.8518	k_2 = 5.0892	99.33	<0.0001
	75	k_1 = 3.4782	k_2 = 5.3580	99.94	<0.0001
	100	k_1 = 5.1812	k_2 = 5.3398	99.62	<0.0001
	Mean			*99.40*	*<0.0001*

The first-order kinetic model had the best correlation across all five evaluated ultrasonic power levels. The correlation coefficient (R^2) for this model consistently exceeded those of alternative models, varying from 0.99 to 1.00. The Peleg, modified Peleg, and power-law models exhibited R^2 values typically near 0.95, indicating a strong fit to the data. The Elovich model exhibited R^2 values approximately 0.76, indicating it provided the least accurate fit for the data. The results indicate that the extraction dynamics of polyphenols and anthocyanins from *Ardisia elliptica* are best described by a first-order diffusion-controlled mechanism. The first-order model asserts that the solute release rate is directly proportional to the concentration gradient between the solute in the solid matrix and the solvent, mirroring the mathematical principles of Fick's law of diffusion. This signifies that the transfer of bioactive compounds mostly occurs through molecular diffusion driven by concentration gradients, which are influenced by the intensity of ultrasonic sound. This impact diminishes resistance to mass transfer and reduces the diffusion pathway, hence accelerating solute release. As ultrasonic power increases, cavitation generates higher shear forces and microstreaming effects. This facilitates the separation of cell fragments and reveals internal solute-dense regions to the solvent. This mechanism clarifies the fast solute release noted during the initial extraction phase, defined by external diffusion (Loan, Thuy, & Van Tai, 2023). The Peleg and modified Peleg models provide significant attributes that define both the initial extraction rate ($1/k_1$) and the equilibrium extraction capacity (k_2). In diffusion processes, the Peleg constant k_1 indicates the rate of surface solute desorption, whereas k_2 denotes the maximum concentration achievable at equilibrium (Lemus-Mondaca *et al.*, 2021). The decrease of k_1 with increasing ultrasonic intensity indicates that the initial extraction rate accelerates due to enhanced turbulence and interaction between the solvent and the solid. On the other hand, k_2 values that stay the same or change only slightly at higher power levels suggest that once internal diffusion takes over, the extraction reaches a steady state where mass transfer is controlled by solute diffusion through the solid matrix rather than by external film resistance. Therefore, it could be seen that the extraction process comprises three primary diffusion stages: (i) a

rapid initial stage, wherein readily accessible solutes dissolve and desorb from the particle surface; (ii) an intermediate stage, characterized by ultrasound-induced microstreaming and cavitation that facilitate solvent penetration and enhance internal diffusion; and (iii) a concluding equilibrium stage, marked by diminished diffusion gradients and a gradual release of solutes confined within the cell matrix. The alteration in the rate constants from the kinetic models illustrates the variations in these stages. The interpretations correspond with the results of Rakshit, Srivastav and Bhunia (2020a), who demonstrated that the first-order model provided the optimal fit for ultrasound-assisted extraction of punicalagin from pomegranate peel. Loan, Thuy and Van Tai (2023) observed that ultrasonic radiation power significantly influenced the extraction rate of polyphenols from purple rice bran, characterized by a rapid early phase followed by a gradual diffusion-controlled stage. Biswas *et al.* (2023) shown that non-traditional extraction methods, such as ultrasound and microwave irradiation, enhance diffusion and increase the overall recovery of bioactive compounds from fruit and plant by-products. The aggregated findings support the notion that the mechanical effects of ultrasound, such as cavitation, turbulence, and cellular rupture, significantly enhance mass transfer during extraction. This results in increased yields and reduced processing durations. In conclusion, the alterations in kinetic constants and the superior outcomes of the first-order model indicate that diffusion is the primary mechanism facilitating the ultrasound-assisted extraction of *A. elliptica* bioactives. Ultrasonic energy accelerates both external and internal diffusion, reduces the time required to achieve equilibrium, and enhances solvent accessibility. All of these factors enhance the efficiency of extracting bioactive chemicals.

3.2 *Effect of sonication power on the total phenolic content and empirical model kinetics*

The total polyphenol content (TPC) of *Ardisia elliptica* extracts increased rapidly during the first 10–15 minutes of extraction for all ultrasonic power levels, indicating that mass transfer was initially controlled by the release of surface-bound compounds. During this early phase, sonication markedly enhanced extraction efficiency: at 5 minutes, TPC values ranged from 27.23 mg GAE/g (0% amplitude) to 55.21 mg GAE/g (50% amplitude), almost doubling the yield compared with the non-sonicated condition. This acceleration is attributed to ultrasonic cavitation, which disrupts the plant cell walls, improving solvent penetration and facilitating solute diffusion (Pogorzelska-Nowicka, Hanula, & Pogorzelski, 2024). Between 10 and 25 minutes, the extraction rate began to slow as easily
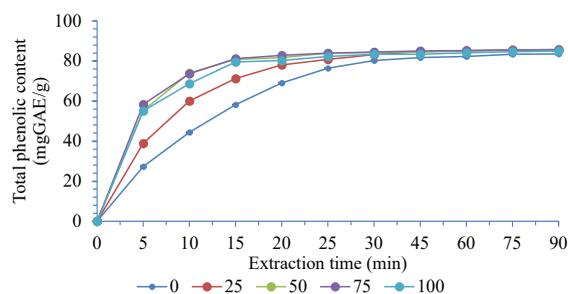

Figure 2. Effect of sonication conditions on total polyphenol content of Pilangkasa fruit.

accessible polyphenols were depleted and internal diffusion became the rate-limiting step. Although differences among amplitudes persisted, the gap gradually narrowed; by 30 minutes, all samples achieved TPC values above 83 mg GAE/g, with less than a 2.5% difference between treatments. Beyond this point, increases were minimal, indicating that equilibrium had been reached. The final TPC values after 90 minutes ranged from 83.53 mg GAE/g (0%) to 85.73 mg GAE/g (50%), showing no statistically significant difference between sonicated and non-sonicated samples. These results confirm that ultrasound primarily affects the kinetic behavior—accelerating the initial extraction rate and reducing the time required to reach equilibrium—rather than substantially increasing the overall extraction capacity. In practical terms, moderate amplitudes (50–75%) achieve rapid extraction with high efficiency while avoiding the potential compound degradation that can occur at higher power levels (100%). The principal benefit of increasing ultrasonic power for polyphenols is the decrease in extraction duration, rather than an improvement in the ultimate polyphenol yield (Khan *et al.*, 2025). The findings suggest that moderate ultrasonic power may be adequate for optimizing polyphenol recovery, whereas increased power mainly reduces processing duration without significantly improving polyphenol extraction. Moreover, this also indicates that the maximal recoverable polyphenol content is mostly determined by the raw material's inherent levels, and that traditional extraction methods, given adequate time, may extract nearly all polyphenols. Nonetheless, the critical distinction is that the extraction rate of polyphenols is markedly enhanced by ultrasonication. Kinetic observations indicated that during the initial stages, the ultrasonic sample attained a markedly superior TPC value compared to the untreated sample. The extraction duration required to obtain, for instance, 0.5 mg GAE/g of polyphenol was markedly reduced with escalating ultrasonic power. The first-order model's rate constant k increased by about three times, from roughly 0.08 min^{-1} (0% amplitude) to 0.21–0.22 min^{-1} at 75% power. The sample reached a state of polyphenol saturation more quickly due to ultrasound's facilitation of the polyphenols' quick

Table 2. Empirical model kinetic development for prediction the effect of sonication conditions on the total polyphenol content of Pilangkasa fruit.

Model	Ultrasound amplitude (%)	Model constants		R^2	MSE
$C_t = C_{eq}(1 - e^{-kt})$	0	k = 0.0809	C_{eq} = 0.8479	99.62	0.0003
	25	k = 0.1210	C_{eq} = 0.8545	99.99	<0.0001
	50	k = 0.2104	C_{eq} = 0.8425	99.94	<0.0001
	75	k = 0.2203	C_{eq} = 0.8503	99.87	<0.0001
	100	k = 0.2020	C_{eq} = 0.8312	99.70	0.0002
	Mean			*99.82*	*0.0001*
$C_t = \dfrac{C_{eq}t}{k+t}$	0	k = 1.0161	C_{eq} = 10.8791	98.10	0.0016
	25	k = 0.9684	C_{eq} = 6.0153	98.87	0.0009
	50	k = 0.9046	C_{eq} = 2.6232	99.17	0.0006
	75	k = 0.9098	C_{eq} = 2.4429	99.89	0.0003
	100	k = 0.8949	C_{eq} = 2.7731	99.32	0.0005
	Mean			*99.07*	*0.0008*
$C_t = E\ln(t) + a$	0	E = 0.2205	a = -0.0239	91.33	0.0036
	25	E = 0.1689	a = 0.2099	86.35	0.0036
	50	E = 0.0955	a = 0.4901	74.13	0.0025
	75	E = 0.0919	a = 0.5126	77.63	0.0019
	100	E = 0.0987	a = 0.4663	78.17	0.0021
	Mean			*81.52*	*0.0027*
$C_t = B\,t^n$	0	B = 0.2449	n = 0.3119	92.81	0.0061
	25	B = 0.3710	n = 0.2161	94.18	0.0047
	50	B = 0.5470	n = 0.1159	96.46	0.0025
	75	B = 0.5641	n = 0.1107	97.29	0.0020
	100	B = 0.5264	n = 0.1225	96.80	0.0022
	Mean			*95.51*	*0.0035*
$C_t = \dfrac{t}{(k_1 + k_2 t)}$	0	k_1 = 10.7073	k_2 = 0.9842	98.10	0.0016
	25	k_1 = 6.2115	k_2 = 1.0326	98.88	0.0009
	50	k_1 = 2.8997	k_2 = 1.1054	99.17	0.0006
	75	k_1 = 2.6850	k_2 = 1.0990	99.53	0.0003
	100	k_1 = 3.0988	k_2 = 1.1174	99.44	0.0005
	Mean			*99.02*	*0.0008*

migration from fruit puree to the solvent (Pogorzelska-Nowicka, Hanula, & Pogorzelski, 2024).

TPC kinetic modeling demonstrated that the first-order model most precisely depicted the process, like the extraction yield. The R^2 values for the first-order model applied to TPC data across all power levels were remarkably high (above 0.99), above the Elovich model (about 0.82) and almost exceeding the Peleg and power-law models (Table 2). During the extraction of polyphenols from peppermint leaves, the first-order model exhibited the best R^2 (approximately 0.984) for both dry matter yield and total polyphenol yield, whereas the Elovich model demonstrated the lowest R^2 (approximately 0.73) (Pavlić *et al.*, 2023). The kinetics of polyphenol extraction followed a first-order model, suggesting that the release of polyphenols from the material matrix was controlled by diffusion through the cell membrane, consistent with the mechanical comprehension of the extraction process.

Lazar *et al.* (2016) investigated the extraction kinetics of polyphenols from polyphenols from *Picea abies* bark utilizing the ultrasound technique. This study indicating that increased power of sonication conditions correlated with a more rapid extraction rate. Nadeem *et al.* (2022) reported that sonication resulted in an increase in total phenol, flavonoids, free radical scavenging activity, antioxidant capacity, and reducing power in fruit juices.

When the ultrasound power increased, more non-polyphenolic compounds, like sugars, proteins, and soluble starches, were released into the solution. This made the total solids extracted higher and the polyphenol concentration in the extract lower (Faisal Manzoor *et al.*, 2023). Therefore, to reach the specific goal of getting more extract or increasing the concentration of bioactives, it is very important to choose the sustaible degree of ultrasonic power. Moderate ultrasound power could efficiently disturbed tissue to recieve polyphenols while limiting the co-extraction of undesired compounds, hence boosting the relative purity of the extract. This is the reason that the ultrasonic sample got near to polyphenol saturation point in the first 30 minutes, whereas the control sample could be took longer to get a similar content of polyphenol.

3.3 Effect of sonication power on the total anthocyanin content and empirical model kinetics

Anthocyanin, the distinctive purple pigment in Pilangkasa fruit, functions as a notable antioxidant (Yukongphan *et al.*, 2013). The study indicated that the total extractable anthocyanin content remained largely unchanged by variations in ultrasonic power. Under the specified settings, the final anthocyanin concentration stabilized between 1.42 and 1.46 mg/100 g after 90 minutes across all amplitudes, indicating only minor variations due to sonication. This yield is rather low in comparison to fruits rich in anthocyanins. The low anthocyanin content in *A. elliptica* may be attributed to its inherent characteristics or to suboptimal extraction conditions, as these pigments are susceptible to heat and sound. Enhancing the solvent composition, pH, and duration of sonication could further optimize recovery and demonstrate the efficacy of this fruit as a source of anthocyanins. The minimal differences in anthocyanin yield at various ultrasonic amplitudes can be explained by kinetic theories. The first-order model posits that the extraction rate constant (k) governs the speed at which equilibrium is attained, while the equilibrium concentration (C_∞) indicates the maximum quantity that may be extracted. Ultrasonication primarily enhances k by accelerating mass transfer and diffusion during the initial stages of extraction. However, it does not significantly alter C_∞, as the total concentration of anthocyanins inside the plant matrix remains constant. Although increased amplitudes accelerate the attainment of equilibrium, the final concentration of anthocyanins after 90 minutes remains very consistent across all treatments. This outcome confirms that ultrasound affects the kinetic rate instead of the extraction capacity, consistent with the expectations of the first-order model and previous studies (Rakshit, Srivastav, & Bhunia, 2020a). Ahmad-Qasem *et al.* (2013) indicated that ultrasound energy application presented a viable alternative for enhancing the extraction of phenolic compounds from olive leaves. The ultrasound effect primarily depended on the effective ultrasonic power applied to the medium, influenced by both the electric power supplied and the coupling efficiency between the emitter surface and the extracting medium (Chemat *et al.*, 2017). The anthocyanin extraction rate significantly increased with higher ultrasonic power, despite the total anthocyanin quantity remaining constant. The first-order model demonstrates that the rate constant k increased from approximately 4.86 min^{-1} (0% sonication) to 12.8 and 17.5 min^{-1} at 50% and 75% power, respectively, followed by a slight decrease to 15.5 min^{-1} at 100% power. This suggested that sonication enhances the swift extraction of anthocyanins from the fruit matrix, with most
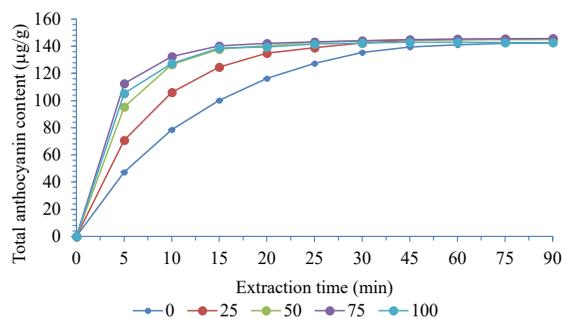

Figure 3. Effect of sonication conditions on total anthocyanin content of Pilangkasa fruit.

anthocyanins being released in the initial minutes. At 75% power, the speed reached its maximum; significantly, an increase to 100% did not improve the speed and frequently led to a decrease. The sensitivity of anthocyanins likely resulted in their partial degradation during the extraction process (Idir *et al.*, 2025), attributed to high anthocyanin concentration, thereby reducing both the extraction rate and the equilibrium anthocyanin content. Increased ultrasonic intensities lead to reduced anthocyanin production; in particular, anthocyanin-rich solutions exposed to high-power ultrasound showed color degradation resulting from the structural breakdown of anthocyanins (Li *et al.*, 2022). Thus, optimizing anthocyanin recovery is crucial for enabling rapid extraction while maintaining the integrity of the substances involved.

The kinetic model indicates that, similar to polyphenols, the first-order model most effectively describes the anthocyanin extraction process, demonstrating R^2 values of about 0.98–0.99 across all cases, significantly outperforming the Elovich model, which shows values between approximately 0.73 and 0.92. The anthocyanin dissolving process is justifiable as it follows the principles of membrane diffusion kinetics (Silva *et al.*, 2017). The first-order model exhibits a satisfactory overall fit; however, the slight decrease in C_{eq} of anthocyanin at 100% power suggests that additional degrading variables should be considered. Thermal or oxidative degradation models may be incorporated into the analysis. This study acknowledges that the peak anthocyanin content is approximately 1.44 mg/100g, and the observed decline at elevated power levels is valid. The mechanism through which ultrasound influences anthocyanins encompasses both beneficial and detrimental elements. Cavitation effects alter tissue architecture, facilitating the rapid release of anthocyanins from the bran layer, surpassing natural diffusion rates. The disintegration of microbubbles results in localized temperature increases surpassing 5000 K and leads to the formation of free radicals (HO·, H·) via the dissociation of water molecules (Yasui, 2022). Anthocyanins exhibit a high potential to oxidation by free radicals and show instability at elevated temperatures, resulting in degradation

when subjected to excessive or prolonged ultrasound exposure (Arruda *et al.*, 2021). Ultrasound markedly reduces the time required for anthocyanin extraction; however, selecting the correct power level is essential to preserve the compound's purity. The findings indicate that a power range of 50–75% is optimal, facilitating nearly complete recovery of anthocyanins

in the bran and expediting the process before substantial deterioration occurs. This conclusion aligns with recent research indicating that ultrasonic extraction serves as a rapid and efficient technique for obtaining anthocyanins; however, it is essential to meticulously regulate the processing parameters to maintain this significant pigment.

Table 3. Empirical model kinetic development for prediction the effect of sonication conditions on the total anthocyanin content of Pilangkasa fruit.

Model	Ultrasound amplitude (%)	Model constants		R^2	MSE
$C_t = C_{eq} (1 - e^{-kt})$	0	k = 4.8597	C_{eq} = 1.4447	99.86	0.0003
	25	k = 7.9112	C_{eq} = 1.4507	99.99	<0.0001
	50	k = 12.7794	C_{eq} = 1.4423	99.97	<0.0001
	75	k = 17.4575	C_{eq} = 1.4396	99.83	0.0004
	100	k = 15.4808	C_{eq} = 1.4198	99.85	0.0003
	Mean			*99.90*	*0.0002*
$C_t = \dfrac{C_{eq}t}{k+t}$	0	k = 1.7284	C_{eq} = 10.7867	98.66	0.0033
	25	k = 1.6275	C_{eq} = 5.2889	98.94	0.0024
	50	k = 2.5602	C_{eq} = 1.5463	99.21	0.0017
	75	k = 1.5415	C_{eq} = 1.5101	99.81	0.0004
	100	k = 1.8653	C_{eq} = 1.4999	99.59	0.0008
	Mean			*99.24*	*0.0002*
$C_t = E \ln(t) + a$	0	E = 0.3727	a = -0.0295	92.87	0.0084
	25	E = 0.2660	a = 0.4415	84.69	0.0101
	50	E = 0.1601	a = 0.8518	73.65	0.0072
	75	E = 0.1080	a = 1.0485	76.51	0.0028
	100	E = 0.1230	a = 0.9705	73.55	0.0043
	Mean			*80.25*	*0.0066*
$C_t = Bt^n$	0	B = 0.4190	n = 0.3109	93.78	0.0151
	25	B = 0.679	n = 0.2161	94.18	0.0047
	50	B = 0.5470	n = 0.1159	96.46	0.0025
	75	B = 0.5641	n = 0.1107	97.29	0.0020
	100	B = 0.5264	n = 0.1225	96.80	0.0022
	Mean			*95.70*	*0.0053*
$C_t = \dfrac{t}{(k_1 + k_2 t)}$	0	k_1 = 6.2413	k_2 = 0.5785	98.66	0.0032
	25	k_1 = 3.2497	k_2 = 0.6145	98.94	0.0024
	50	k_1 = 1.6556	k_2 = 0.6467	99.21	0.0017
	75	k_1 = 1.0208	k_2 = 0.6622	99.81	0.0004
	100	k_1 = 1.2437	k_2 = 0.6667	99.59	0.0008
	Mean			*99.24*	*0.0017*

3.4 Development of ANN model - machine-learning kinetic model

Figure 4 illustrates the ANN architectures for each output factor (extraction yield, TPC, anthocyanin content) and sonication parameters (amplitude and duration), together with the corresponding coefficients of determination for each output variable. The R^2 values for training, testing, and validation, along with the number of hidden layer neurons (10 neurons), were utilized to select the most effective ANN design to mitigate overfitting, as shown by recent literature references (Loan *et al.*, 2025; Loan, Vinh, & Tai, 2024; Luangsakul *et al.*, 2025). The ultrasound-assisted extraction of Pilangkasa fruit demonstrated that the artificial neural networks (ANNs) designed to predict

recovery characteristics yielded the most favorable training, testing, and validation outcomes, followed by those developed for the simultaneous prediction of extraction yield, total phenolic content (TPC), and anthocyanin levels. The multilayer perceptron (MLP) Artificial Neural Network, designated as MLP 2-10-3, is deemed optimal for modeling the extraction yield of antioxidant compounds in extracts, exhibiting $R_{training}$ = 0.99989, R_{test} = 0.99986, and $R_{validation}$ = 0.9999, based on the extraction dataset. The MSE values of training, test, validation set were 0.5285, 0.6894, 1.0896, respectively. It comprises two neurons in the input layer, ten neurons in the hidden layer, and three neurons in the output layer. The ANN model has recently been able to accurately predict a number of
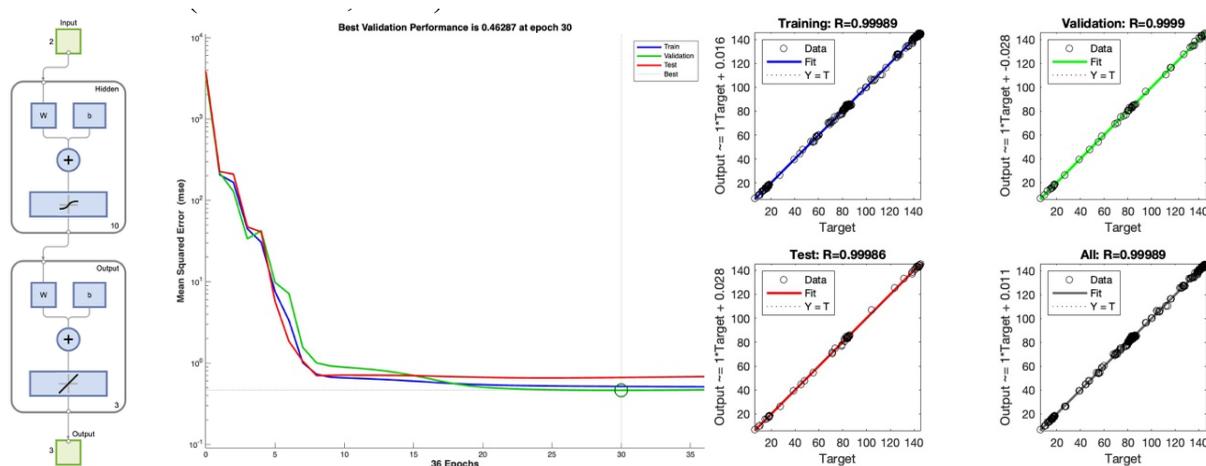
Figure 4. ANN model prediction of effect of sonication conditions on the recovery efficiency of bioactive compounds from Pilangkasa fruit

of processes, such as the hot air drying kinetics of garlic slices (Loan, Vinh, & Tai, 2024), the ultrasound-assisted extraction of polyphenols from purple rice bran (Loan, Vinh, & Tai, 2024), and the drying kinetics and thermal degradation of instant germinated rice (Loan *et al*., 2025).

3.5 Comparsion prediction capacity of between empirical and machine-learning kinetic model

The research findings indicate that the discrepancy between the anticipated and actual values of the first-order empirical model is approximately 2–5%, whereas the artificial neural network (ANN) model exhibits a discrepancy of only about 1–2%. The ANN model can precisely forecast the impact of alterations in extraction parameters on the efficiency of antioxidant recovery. The correlation coefficient (R) of the ANN model surpassed that of the empirical model, indicating superior data fit of the ANN model. The ANN model can simultaneously simulate and predict many outputs inside a single framework. The empirical model, on the other hand, necessitates separate models for each index or extraction condition. ANN. Qian *et al*. (2025) developed an artificial neural network (ANN) capable of simultaneously predicting extraction yield, total phenolics, total flavonoids, and antioxidant activity (DPPH and ABTS). This approach is superior to constructing individual regression equations for each output metric. This indicates that the ANN model is adaptable and more proficient at emulating intricate extraction procedures.

Conclusions

This work aimed to extract polyphenol- and anthocyanin-rich bioactive compounds from

Pilangkasa fruit (Ardisia elliptica Thunb.), a raw material abundant in antioxidants that remains underutilized. The researchers employed ultrasound-assisted extraction (UAE) at varying intensities utilizing a 60% food-grade ethanol solvent. The findings indicated that an ultrasonic power level of 50–75% achieved both high efficiency and recovery rates, with minimal degradation of active material. The concentrations of polyphenols and anthocyanins remained virtually unchanged across all power levels. The first-order kinetic model effectively characterized the process ($R^2 > 0.98$), whereas the artificial neural network (ANN) model exhibited diminished prediction errors (1–2% compared to 2–5%) and the capability to simultaneously forecast multiple parameters, indicating its significant potential for process optimization and control. These findings provide scientists with a rationale to develop an environmentally friendly, energy-efficient, and food-safe extraction method for Pilangkasa, while also unveiling novel applications for various other plant materials rich in antioxidants. This fosters the trend of sustainable production and clean-label products within the food and pharmaceutical sectors. Moreover, this study provides a useful baseline for understanding the extraction behavior of *Ardisia elliptica*. Although only ultrasonic power was examined, the results highlight the potential of this species as a bioactive source and suggest that further optimization of variables such as solvent composition, temperature, and time could enhance anthocyanin recovery.

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