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Microwave-assisted extraction of anthocyanin from "Cấm" rice bran using natural deep eutectic solvents: A kinetic study by empirical models

Extracción asistida por microondas de antocianinas del salvado de arroz "Cấm" utilizando solventes eutécticos profundos naturales: Un estudio cinético mediante modelos empíricos

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Abstract

Rice bran, particularly pigmented varieties such as "Cấm" rice, is an abundant agricultural by-product rich in anthocyanins and phenolic compounds with notable antioxidant and health-promoting properties. When combined with natural deep eutectic solvents (NADES), a class of green solvents with high polarity and strong hydrogen-bonding capacity, Microwave-assisted extraction (MAE) could be further enhanced recovery yields while providing a more sustainable alternative to organic solvents. This study investigated the effects of microwave power and extraction time on the recovery of total phenolic content (TPC) and anthocyanins from "Cấm" rice bran using a choline chloride–ethylene glycol (NADES system). Empirical kinetic modeling was applied to evaluate the extraction process, with models such as first-order, two-side, Peleg, Elovich, and power-law tested for predictive accuracy. Results indicated that both TPC and anthocyanin recoveries followed rapid initial release phases, approaching equilibrium within 5–10 minutes at higher microwave power. The first-order and two-side kinetic models provided the best fit ($R^2 > 0.99$), highlighting distinct fast and slow extraction phases. These findings confirm MAE–NADES as an efficient and sustainable strategy for valorizing pigmented rice bran and offer valuable insights for optimizing functional food and nutraceutical production.

Keywords: rice bran, extraction, microwave, modeling, kinetic.

Resumen

El salvado de arroz, particularmente las variedades pigmentadas como el arroz "Cấm", es un subproducto agrícola abundante rico en antocianinas y compuestos fenólicos con notables propiedades antioxidantes y beneficiosas para la salud. Cuando se combinan con solventes eutécticos profundos naturales (NADES), una clase de solventes verdes con alta polaridad y fuerte capacidad de formación de enlaces de hidrógeno, la extracción asistida por microondas (MAE) podría mejorar aún más los rendimientos de recuperación mientras proporciona una alternativa más sostenible a los solventes orgánicos. Este estudio investigó los efectos de la potencia del microondas y el tiempo de extracción en la recuperación del contenido total de fenoles (TPC) y antocianinas del salvado de arroz "Cấm" utilizando un sistema de cloruro de colina-etanol (sistema NADES). Se aplicó modelado cinético empírico para evaluar el proceso de extracción, con modelos como el de primer orden, de dos lados, Peleg, Elovich y de ley de potencias probados para su precisión predictiva. Los resultados indicaron que tanto las recuperaciones de TPC como de antocianinas siguieron fases iniciales de liberación rápida, acercándose al equilibrio en 5–10 minutos a mayor potencia de microondas. Los modelos cinéticos de primer orden y de dos lados proporcionaron el mejor ajuste ($R2 > 0.99$), destacando fases de extracción rápidas y lentas distintas. Estos hallazgos confirman que MAE–NADES es una estrategia eficiente y sostenible para la valorización del salvado de arroz pigmentado y ofrecen valiosos conocimientos para optimizar la producción de alimentos funcionales y nutracéuticos.

Palabras clave: salvado de arroz, extracción, microondas, modelado, cinética.

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1 Introduction

Rice bran is an important by-product in the rice milling process, accounting for about 8–10% of the rice grain weight, but is rich in nutrients and biological compounds (Sapwarobol, Saphyakhajorn, & Astina, 2021; Van Tai, Minh, & Thuy, 2023). In particular, colored rice bran – especially the Vietnamese "Cấm" rice variety – contains high levels of anthocyanins and polyphenols, creating a characteristic purple color while providing powerful biological activities (Loan, Vinh, & Tai, 2024b). Anthocyanins are a group of water-soluble compounds that contribute to natural coloring and have many health benefits that have been proven by experimental and clinical studies, including antioxidant, cardiovascular protection, anti-inflammatory, and potential prevention of some chronic diseases such as diabetes and cancer (Mattioli *et al*., 2020). In addition to anthocyanins, rice bran is also a source of polyphenols, tocopherols, and γ-oryzanol, which are considered important functional compounds in the food and pharmaceutical industries (Manzoor *et al*., 2023). However, the optimal extraction of these compounds is challenging due to their tight binding in the cell structure and their sensitivity to environmental factors such as temperature, pH, and light (Molina *et al*., 2023). Therefore, the development of efficient, sustainable, and environmentally friendly extraction technologies to recover anthocyanins and polyphenols from rice bran by-products is of both scientific and practical significance.

Conventional extraction methods such as organic solvent extraction, Soxhlet or recirculation have certain effectiveness but often require long time, consume toxic solvents and have low efficiency (Bitwell et al., 2023). Especially for anthocyanins, which are very sensitive to high temperature and oxidizing environment, these methods easily lead to decomposition or loss of biological activity. In addition, the extraction efficiency is also limited by the slow diffusion of biological compounds through plant cell membranes (Obando-Galicia, Martínez-de Jesús, & Totosaus, 2024).

More advanced techniques such as ultrasound-assisted extraction (UAE), supercritical CO_2, or enzyme-assisted extraction have been applied to improve the yield, but each method has its own limitations as UAE can cause active substance degradation if the power is too high, supercritical CO_2 requires large equipment costs, and enzyme-assisted is often time-consuming and the enzyme cost is high (Mungwari *et al*., 2025). Therefore, there is still a need for more efficient technologies that can shorten the time, save solvents, and minimize environmental impact. Microwave-assisted extraction (MAE) has emerged as a promising technology (Fernandez-Avalos *et al*., 2025; Thuy *et al*., 2022). MAE uses microwave-frequency electromagnetic energy to directly heat polar molecules in the sample and solvent, thereby generating internal heat instead of external heat transfer (Yedhu Krishnan & Rajan, 2016). This mechanism leads to local heating in the plant structure, causing the disruption of membranes and cell walls, rapidly releasing biological compounds. At the same time, the internal heating significantly shortens the extraction time and reduces the amount of solvent required compared to traditional methods (Mungwari *et al*., 2025). The efficiency of MAE in the extraction of polyphenols and flavonoids from various plant sources has been demonstrated. Dong *et al*. (2014) reported that MAE vanillin from Vanilla planifolia achieved significantly higher yields than other methods due to faster extraction kinetics. Similarly, Pavlić *et al*. (2023) also reported that MAE shortened the extraction time from hours to minutes while retaining the bioactivity while extracting polyphenols from mint leaves. These results suggest a great potential for the application of MAE for anthocyanin-rich colored rice bran.

One of the important trends today is to replace toxic organic solvents with green solvents. Among them, natural eutectic solvents (NADES) are of interest due to their outstanding properties as environmentally friendly, biodegradable, low cost, and the ability to form strong hydrogen bonds with biological compounds (Asritha *et al*., 2025). NADES are often made from a mixture of natural compounds such as choline chloride, organic acids, sugars, polyols, etc. in appropriate proportions. In the study by Ratanasongtham *et al*. (2024), NADES combined with ultrasound helped increase the efficiency of extracting antioxidants from Thai colored rice bran compared to ethanol. Similarly, Kayahan and Saloglu (2020) showed that NADES combined with microwaves was able to effectively extract polyphenols from artichokes, while minimizing the use of chemical solvents. This proves that NADES is not only a safe alternative solvent but can also play a protective role for sensitive compounds such as anthocyanins thanks to the hydrogen-rich environment, limiting thermal and oxidative degradation.

To optimize the MAE process combined with NADES, building a kinetic model is necessary. Mathematical models such as first-order, two-side, Peleg, Elovich, and power-law are commonly applied to describe the extraction process (Kayahan & Saloglu, 2020; Tirpanci Sivri, 2024). Choosing the appropriate kinetic model is important for predicting yield, determining optimal conditions, and scaling up the technology. In addition to traditional mathematical models, the application of artificial intelligence, especially artificial neural networks (ANN), is

becoming a trend in research and optimization of food technology processes. Integrating ANN into the study of anthocyanin extraction from "Cẩm" rice bran using MAE–NADES not only helps to evaluate the suitability of the kinetic model but also opens up the possibility of predicting and optimizing process conditions with high reliability. Although there are many studies applying MAE and NADES in the extraction of biological compounds from plant materials, studies focusing on colored rice bran – especially the "Cẩm" variety of Vietnam – are still limited. Moreover, most of the previous studies mainly evaluated the extraction efficiency without incorporating detailed kinetic analysis to describe and predict the process. This leads to a gap in understanding the mechanism of microwave and NADES effects on the rate and extent of anthocyanin and polyphenol recovery from rice bran. Based on the above context, this study was conducted with the following objectives: (i) to evaluate the effects of microwave power and time on the recovery efficiency of total polyphenol (TPC) and anthocyanin from "Cẩm" rice bran using NADES; (ii) to develop and compare different kinetic models to determine the most suitable descriptive model; and (iii) to clarify the mechanism of microwave and NADES effects on extraction efficiency. The research results are expected to contribute to the database for the effective utilization of agricultural by-products, and at the same time open up the direction for the development of green extraction processes for the functional food and pharmaceutical industries.

2 Materials and methods

2.1 Materials

"Cẩm" rice bran was obtained following the milling and polishing processes at a local enterprise in Tien Giang province, Vietnam. The defatted rice bran was milled to pass through an 80 mesh screen for further extraction. The powder was stored in a dark, airtight bag at 4°C until the extraction was performed.

2.2 Microwave-assisted extraction in NADES solution

This extraction experiment utilized various microwave power levels (90, 150, 300, 600, 800 W). An Electrolux microwave oven from Korea was utilized to conduct the extraction process. Extractions were conducted at a solid–liquid ratio of 1:10 (w/v). The extraction solvent is a mixture of choline chloride and ethylene glycol (Ch:Eg) in a 1:2 ratio (mol/mol), combined with 20% water (Ratanasongtham *et al*., 2024). The crude extracts were promptly centrifuged at 10,000 rpm for 1 minute and subsequently filtered through filter paper under vacuum (V-700, Büchi, Switzerland) immediately following extraction. The extracts were gathered in glass jars and preserved at 4°C until subsequent analysis. The crude liquid extract was subjected to vacuum evaporation and subsequently dried to ascertain the total extraction yield. The data were presented as the percentage of total extractable solids per 100 g of dry sample (%, w/w).

The dried extract was reconstituted with 80% methanol before to total phenolic content (TPC) examination. The total phenolic content of the extract was assessed using the method outlined by Wanyo, Meeso and Siriamornpun (2014). In summary, 300 μL of extract was combined with 2.25 mL of 10% Folin–Ciocalteu reagent and left to incubate at room temperature for 5 minutes, after which 2.25 mL of sodium carbonate solution (60 g/L) was incorporated into the mixture. Following 90 minutes at ambient temperature, absorbance was quantified at 725 nm utilizing a spectrophotometer. Results were presented as milligrams of gallic acid equivalents per gram of dried material (mg GAE/g).

The total anthocyanin content (TAC) was assessed using the pH differential approach (Loan, Vinh, & Tai, 2024b), which relies on the structural alterations in the chemical forms of anthocyanin and absorbance measurements at pH 1.0 and 4.5. Crude extracts were individually diluted with 0.025 M hydrochloric acid–potassium chloride buffer (pH 1) and 0.4 M sodium acetate buffer (pH 4.5). Each sample was diluted with buffers to get an absorbance measurement ranging from 0.2 to 1.4. The absorbance of the mixture was quantified at λvis-max and 700 nm utilizing a UV-Vis spectrophotometer (UV1601; Shimadzu, Kyoto, Japan). The total anthocyanin content was quantified as microgram equivalents of cyanidin-3-glucoside per 100 g (μgCE/100g).

2.3 Kinetic modelling of the MAE of TPC and extraction yield of Cẩm rice bran

This work employed five mathematical models to analyze the experimental data of TPC and extraction yield (Table 1). These models were employed for the kinetic analysis of extraction from plant materials (Kayahan & Saloglu, 2020; Kurtulbaş *et al*., 2022; Pavlić *et al*., 2023). The model's fitness will be determined by the coefficient of determination (R^2 value).

2.4 Data analysis

STATGRAPHICS Centurion XV.I was utilized for nonlinear regression analysis. The concordance between the experimental data and the models was evaluated using mean squared error (MSE) and the

Table 1. Selection model for this study.

Model name	Model equation	Reference
First-order model	$C_t = C_{eq}\ (1- e^{-kt})$	(Yedhu Krishnan & Rajan, 2016)
Two-side kinetic model	$C_t = C_{eq}[1-[F.e^{-kt}]-[(1-F).e^{-vt}]]$	(Harouna-Oumarou *et al*., 2007)
Elovich's model	$C_t = E\ ln(t) + a$	(Dong *et al*., 2014)
Power-law model	$C_t = Bt^n$	(Dong *et al*., 2014)
Peleg's model	$C_t = \frac{t}{(k_1+k_2t)}$	(Kayahan & Saloglu, 2020)

Note: C_t is the solute concentration of TPC (mg GAE/g) or extraction yield (%) at time (t); C_{eq} is its concentration at equilibrium; k, k_1, k_2, E, a, B, n are model constants.

correlation coefficient (R^2). A low mean squared error, and a high R-squared value indicate a strong fit (Dong *et al*., 2014).

3 Results and discussion

3.1 Effect of extraction conditions on the recovery of TPC from "Cấm" rice bran and model development

The experimental results indicated that the total polyphenol content (TPC) increased significantly during the initial stages of the extraction process, eventually stabilizing at a saturated level in the later stages (Figure 1). The total polyphenol content increased significantly to 43-60 mg GAE/g after 3 minutes of extraction, contingent upon the microwave power utilized. After 3 minutes, at a microwave power of 90 W, the TPC reached approximately 43.6 mg GAE/g, while at a microwave power of 600 W, the TPC content was 59.8 mg GAE/g. Enhancing microwave power accelerated the extraction process. At 600 W, the TPC achieved its peak level (61–62 mg GAE/g) within 7.5–10 minutes, whereas at a lower microwave power of 90 W, it required approximately 30 minutes to attain the same TPC value. These values were higher than those reported in the study using 60% ethanol as the solvent at the same microwave power, while requiring a shorter extraction time to reach peak values (Loan, Tai, & Thuy, 2023). In spite of the variations in extraction rates, the maximum TPC achieved at medium to high power levels was consistently around 61 to 63 mg GAE/g. At 800 W, the maximum total phenolic content (TPC) showed a slight decrease compared with that at 600 W (approximately 61.3 versus 62.7 mg GAE/g) and continued to decline after reaching its peak. This reduction was approximately 3% relative to the peak value. This suggests potential degradation of polyphenols due to excessive microwave power or prolonged extraction times. The observed rapid increase and subsequent decrease in TPC indicates a two-stage extraction process. This process begins with a swift release of

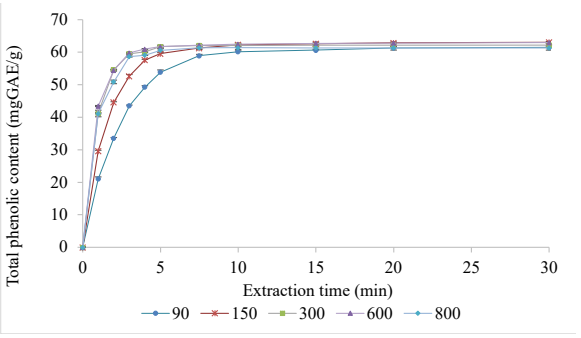

Figure 1. Effect of different microwave levels on the recovery yield of TPC from "Cấm" rice bran.

readily accessible phenolic compounds, which is then followed by a gradual reduction in the extraction rate as diffusion equilibrium is reached.

The enhancement in TPC extraction efficiency due to microwaves and NADES solvent can be attributed to the local thermal effect and the high polarity of the solvent system (Eliazer Nelson & Venkatachalam, 2025; Zhang *et al*., 2022). The interaction of microwave waves with polar molecules, including water and NADES components, induces rapid vibration and heat generation within the sample. The localized heat within the raw material elevates pressure, resulting in tissue breakdown and the disruption of plant cell wall structures. Consequently, phenolic compounds are liberated from the cellular matrix and exhibit enhanced diffusion into the solvent (Eliazer Nelson & Venkatachalam, 2025). Increased temperature concurrently decreases the viscosity and surface tension of NADES solvent, enhances the wettability of the raw material, and facilitates the migration of compounds into the solvent (Sahal et al., 2025). NADES solvent, composed of choline chloride and ethylene glycol with 20% water, exhibits a high dielectric constant and significant hydrogen bonding capacity, which enhances its ability to absorb microwaves and dissolve polar polyphenols effectively (Sahal *et al*., 2025). NADES can extract polyphenols at levels comparable to or exceeding those of conventional organic solvents, making it appropriate for environmentally friendly extraction methods. Excessive microwave power can result in excessive heating, which may cause partial decomposition of target compounds (şen *et al*., 2025).

Table 2. Empirical model kinetic development for prediction the effect of microwave power on the extraction yield of "Cấm" rice bran antioxidants.

Model	Microwave	Model constants		R^2	MSE
Two-side kinetic model $C_t = C_{eq}[1-[F.e^{-kt}]-[(1-F).e^{-vt}]]$	90	C_{eq} = 0.613	F = 1.004	99.96	<0.0001
		k = 24.468	v = 7.525		
	150	C_{eq} = 0.630	F = 0.988	99.98	<0.0001
		k = 38.719	v = 4.260		
	300	C_{eq} = 0.614	F = 1.004	99.97	<0.0001
		k = 69.751	v = -1.860		
	600	C_{eq} = 0.607	F = 1.009	99.91	<0.0001
		k = 65.389	v = -1.909		
	800	C_{eq} = 0.597	F = 1.010	99.70	<0.0001
		k = 62.850	v = -1.355		
First order model $C_t = C_{eq}$ (1- e^{-kt})	90	k = 24.615	C_{eq} = 0.6132	99.96	<0.0001
	150	k = 37.651	C_{eq} = 0.6252	99.96	<0.0001
	300	k = 64.905	C_{eq} = 0.6195	99.96	<0.0001
	600	k = 68.305	C_{eq} = 0.6225	99.85	<0.0001
	800	k = 62.155	C_{eq} = 0.6102	99.68	0.0001
Elovich's model C_t = E ln(t) + a	90	E = 0.1196	a = 0.7759	85.49	0.0032
	150	E = 0.0885	a = 0.7575	76.13	0.0031
	300	E = 0.0481	a = 0.6973	60.18	0.0019
	600	E = 0.0465	a = 0.6992	65.59	0.0014
	800	E = 0.0503	a = 0.6913	65.17	0.0017
Power law model $C_t = Bt^n$	90	B = 0.8062	n = 0.2158	78.98	0.0049
	150	B = 0.7684	n = 0.1465	69.49	0.0040
	300	B = 0.6987	n = 0.0772	56.97	0.0020
	600	B = 0.7012	n = 0.0746	62.09	0.0018
	800	B = 0.6935	n = 0.0823	61.25	0.0019
Peleg's model Ct = $\frac{t}{(k_1+k_2t)}$	90	k_1 = 0.0433	k_2 = 1.4546	98.40	0.0007
	150	k_1 = 0.0246	k_2 = 1.4709	98.58	0.0006
	300	k_1 = 0.0116	k_2 = 1.5336	98.92	0.0004
	600	k_1 = 0.0108	k_2 = 1.5287	99.36	0.0003
	800	k_1 = 0.0125	k_2 = 1.5537	99.10	0.0003

The observed peak and subsequent slight decrease in TPC at 800 W may result from the degradation or structural changes of certain polyphenols, particularly anthocyanins, which are thermosensitive components, under elevated temperatures. This finding aligns with the observations of Xue *et al*. (2018) regarding anthocyanin extraction from blueberries, indicating that elevated microwave power enhances cell wall disruption. However, when temperatures surpass 50-60°C, the efficiency of anthocyanin recovery does not improve further due to the initiation of thermal degradation. It is essential to optimize the balance between microwave power and duration to maximize TPC while preserving the integrity of the active ingredient.

Kinetic regression analysis utilizing experimental models indicated that the first-order model and the two-side kinetic model most accurately represented the kinetics of TPC extraction from rice bran in NADES solvent (Table 2). Both models exhibited high correlation coefficients (0.997-0.999) and low mean square error (MSE) values (<0.0001) across all microwave power levels tested. The findings indicated a strong correlation between the data of predicted models and the experimental data (Figure 2). The two-side kinetic model facilitated the differentiation of the fast and slow extraction phases, as outlined in the preceding section. The value of F (kinetic constant) for this model was approximately 1 across all cases (F value reached about 0.99-1.01), indicating that the majority of polyphenols were extracted during the fast phase, aligning with the experimental results presented in Table 1. The Elovich and power-law models produced inconsistent results, evidenced by low R^2 values ranging from approximately 0.6 to 0.85 for the Elovich model. This suggests that the extraction mechanism does not adhere strictly to logarithmic diffusion adsorption or an exponential relationship. The Peleg model, while demonstrating strong correlation coefficients (R^2 = 0.98–0.99),

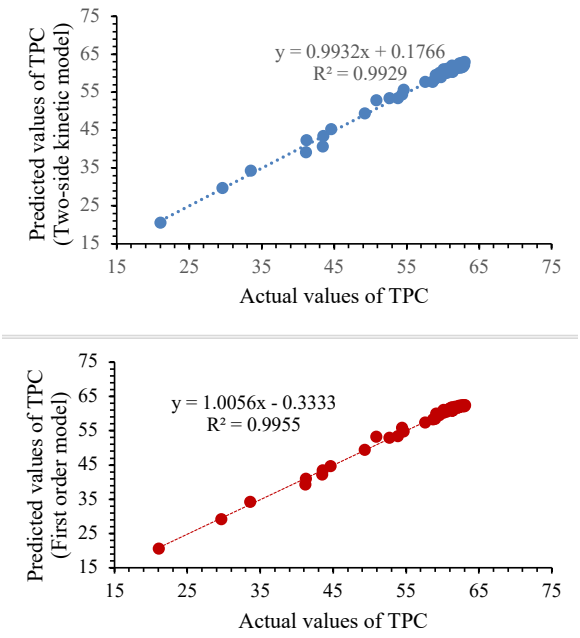

Figure 2. Regression analysis between experiment values and predicted values of TPC by selected models.

exhibited lower performance compared to the first-order/two-level model. The analysis of R^2 and MSE indicates that the first-order model is the most appropriate for characterizing TPC extraction kinetics in this study, consistent with findings from numerous previous studies. Pavlić *et al*. (2023) investigated the kinetics of MAE polyphenols from mint leaves and determined that the first-order model provided the optimal fit, indicated by the highest R^2. They noted that microwave power significantly influenced the rate constant k, whereas the equilibrium value C_{eq} remained relatively stable across varying power levels. Kayahan and Saloglu (2020) employed kinetic models, including first-order and Peleg models, to characterize the MAE process of polyphenols extracted from artichoke leaves, achieving satisfactory fitting results. Dong *et al*. (2014) reported that a two-level model more accurately described the extraction kinetics of vanillin by microwave compared to other models. This finding aligns with the TPC data in this study, which also exhibited clear fast and slow phases.

3.2 Effect of extraction conditions on the recovery of anthocyanin content from "Cấm" rice bran and model development

The anthocyanin content derived from "Cấm" rice bran was significantly influenced by microwave power and extraction duration, exhibiting a trend analogous to total phenolic content, albeit with greater thermal sensitivity. The anthocyanin content initially increased rapidly over time before reaching a near-saturation

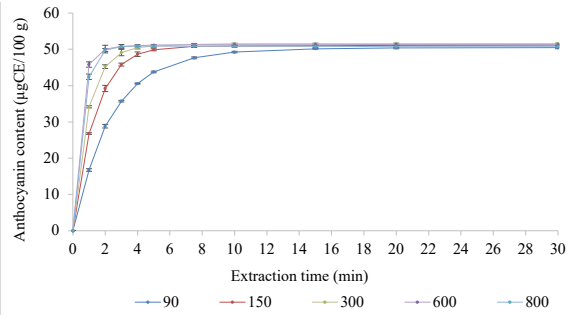

Figure 3. Effect of extraction conditions on the recovery of anthocyanin content from "Cấm" rice bran.

state. At 1 minute, the sample extracted at 600 W yielded approximately 45.8 mg anthocyanin/g, which is nearly three times greater than the sample extracted at 90 W (16.7 μgCE/100g). This indicates that elevated microwave power significantly enhanced the release of anthocyanin from conditions of the extraction process. The extension of extraction time resulted in an increase in anthocyanin content; however, the extraction rate decreased, stabilizing at approximately 50-52 μgCE/100g after a specific duration, contingent upon the microwave power applied. At 600 W, anthocyanin levels approached their maximum (approximately 51.3 μgCE/100g) within 5–7.5 minutes, whereas at 90 W, the same concentration was achieved after 20-30 minutes (Figure 3). Compared with previous studies, the peak anthocyanin content obtained in this study was significant higher than that reported for "Cấm" rice bran extracted using 60% ethanol under microwave irradiation at 500 W (32.55 μg/100 g) (Loan, Vinh, & Tai, 2024a). At the maximum microwave power of 800 W, the anthocyanin content peaked at 50.9 μgCE/100g after approximately 5 minutes, subsequently showing a slight decline by the 30-minute mark. This minor decrease about 1%, while not substantial, indicates that some anthocyanin may have undergone degradation or modification due to the intense and extended microwave exposure (Zhang *et al*., 2025). Conversely, at reduced power levels, there was no observed decrease in anthocyanin content; rather, the extraction curve progressively attained a plateau. The final anthocyanin recovery at power levels of 90-600 W did not show significant variation (ranging from 50-52 μgCE/100g), suggesting that increasing power primarily reduced the time required to achieve equilibrium rather than substantially enhancing the maximum anthocyanin content. This finding aligns with the conclusion of Pavlić *et al*. (2023) that microwave power significantly influenced the extraction rate (k) while minimally impacting the maximum polyphenol recovery value. Efficient anthocyanin extraction necessitates a power level sufficient to rapidly disrupt plant tissue, while remaining below an optimal threshold to prevent

thermal degradation of anthocyanin.

The mechanism of action of microwave combined with NADES demonstrates significant efficacy in anthocyanin recovery; however, a comprehensive understanding of their effects is necessary to optimize the extraction process. Microwaves produce endogenous heat within the sample by oscillating polar molecules, particularly the water vapor present in the capillaries of rice bran (Deng *et al*., 2022). Localized heating swiftly elevates the internal pressure of the cell, resulting in the rupture of the cell membrane and wall, thereby releasing anthocyanins that were initially stored in the vacuole into the solvent (Loan, Tai, & Thuy, 2023). In contrast to exogenous heating methods, microwaves induce internal heating of the raw material and solvent, resulting in localized hot spots and significant temperature gradients at areas of concentrated microwave energy. The hotspots exhibit two specific characteristics: they significantly enhance the release of solute (anthocyanin) and increase the diffusion rate; however, they may also lead to local degradation of anthocyanin if the micro-temperature surpasses its stability threshold (Sahal *et al*., 2025). Anthocyanins are thermally sensitive color compounds that exhibit instability at high temperatures, typically beginning to decompose at approximately 50-70°C, contingent upon pH levels (Idir *et al*., 2025). Consequently, in MAE, it is essential to extract anthocyanins promptly to prevent substantial degradation. The utilization of NADES in this context serves a significant supporting function, as NADES composed of choline chloride and ethylene glycol (with added water) exhibit superior microwave absorption attributed to their high polarity, facilitating the efficient conversion of microwave energy into heat (Tapia-Quirós *et al*., 2024). NADES provide greater stabilization of anthocyanins compared to pure water, as the ethylene glycol-rich environment decreases water activity and mitigates oxidative or hydrolytic degradation reactions. NADES solubilizes anthocyanins via hydrogen bonding and ion-dipole interactions, demonstrating compatibility with Folin–Ciocalteu in TPC analysis, which yields elevated polyphenol content (şen *et al*., 2025; Tapia-Quirós *et al*., 2024). The inclusion of 20% water in NADES decreases solvent viscosity, enhancing its capacity to infiltrate the rice bran structure. Additionally, water's strong microwave absorption generates micropressure, facilitating the expedited release of anthocyanins. The interplay of these factors results in a synergistic effect, with microwaves reducing extraction time and NADES enhancing anthocyanin recovery relative to traditional solvents (Sahal *et al*., 2025; şen *et al*., 2025). Excessive microwave power should be avoided; while a higher release of anthocyanins occurs in a short duration, surpassing their thermal tolerance threshold may lead to a reduction in the actual amount of anthocyanins recovered due to decomposition (Kayahan & Saloglu, 2020; Loan, Vinh, & Tai, 2024b). The selection of the optimal power level, approximately 600 W, and the appropriate extraction time, ranging from 5 to 10 minutes, is crucial for maximizing anthocyanin content while maintaining compound stability. The research findings enhance understanding of the impacts of microwave and NADES, aiding in the advancement of an effective green extraction method for anthocyanin compounds derived from agricultural waste.

The kinetic regression analysis for anthocyanins indicated that the first-order and two-stage models provided the optimal fit (Table 3). The anthocyanin extraction kinetics exhibited a first-order mechanism, analogous to TPC, with a correlation coefficient (R^2) approaching 0.999 across all microwave power levels, in addition to minimal mean squared errors (MSEs). The extraction rate is proportional to the remaining anthocyanin in the raw material, and the process achieves equilibrium exponentially, aligning closely with the experimental data. The two-level model demonstrated a comparable fit (R^2 approximately 0.999) for anthocyanins, indicating that, despite the potential for fast/slow phase separation, the fraction of anthocyanins extracted in the phase nearly fully accounted for the anthocyanins recovered from the raw material. This finding aligns with the observation that microwaves effectively released the majority of anthocyanins in a brief initial period. Thus, selecting a specific time period for the product to achieve maximum anthocyanin content may speed up the subsequent optimization process through the predictive model. The Elovich and power-law models were found to be inadequate for characterizing the anthocyanin extraction data from raw materials. The R^2 value of the Elovich model is approximately 50% at elevated power levels, specifically around 51% at 600 W and 41% at 800 W. This indicates that the logarithmic equation inadequately represents the anthocyanin extraction kinetics during MAE with NADES. The power-law model (exponential form) yields a low R^2 (56-78% depending on the power), suggesting that the anthocyanin extraction rate is not equivalent to a simple exponential function of time. The Peleg model enhanced the correlation between the model and the experimental data (R^2 = 0.98-0.99) relative to the Elovich/power-law model and is frequently employed for two-step processes. However, it demonstrated lower accuracy than the first-order/two-side kinetic model in characterizing the anthocyanin data in this study. The high prediction accuracy is further confirmed by the regression analysis between the experimental and predicted data obtained from the first-order and two-site kinetic models, which shows high regression correlation coefficient values (Figure 4).

Table 3. Empirical model kinetic development for prediction the effect of microwave power on the anothocyanin of "Cẩm" rice bran.

Model	Microwave	Model constants		R^2	MSE
Two-side kinetic model $C_t = C_{eq}[1-[F.e^{-kt}]-[(1-F).e^{-vt}]]$	90	C_{eq} = 0.499	F = 1.001	99.98	<0.0001
		k = 25.069	v = -3.542		
	150	C_{eq} = 0.511	F = 0.999	99.99	<0.0001
		k = 44.532	v = 0.136		
	300	C_{eq} = 0.509	F = 1.002	99.99	<0.0001
		k = 65.183	v = -2.101		
	600	C_{eq} = 0.508	F = 1.002	99.99	<0.0001
		k = 135.723	v = -2.097		
	800	C_{eq} = 0.507	F = 1.003	99.99	<0.0001
		k = 107.426	v = 8.667		
First order model $C_t = C_{eq}$ (1- e^{-kt})	90	k = 24.846	C_{eq} = 0.5023	99.98	<0.0001
	150	k = 44.518	C_{eq} = 0.5108	99.99	<0.0001
	300	k = 64.739	C_{eq} = 0.5137	99.98	<0.0001
	600	k = 134.404	C_{eq} = 0.5113	99.97	<0.0001
	800	k = 108.618	C_{eq} = 0.5087	99.99	<0.0001
Elovich's model $C_t = E \ln(t) + a$	90	E = 0.098	a = 0.636349	86.18	0.0019
	150	E = 0.061	a = 0.603914	68.31	0.0022
	300	E = 0.039	a = 0.578194	60.67	0.0013
	600	E = 0.012	a = 0.531662	51.17	0.0001
	800	E = 0.016	a = 0.534771	41.46	0.0005
Power law model $C_t = Bt^n$	90	B = 0.661	n = 0.2156	77.66	0.0031
	150	B = 0.608	n = 0.1208	66.54	0.0026
	300	B = 0.579	n = 0.0774	56.97	0.0015
	600	B = 0.532	n = 0.0226	52.13	0.0001
	800	B = 0.535	n = 0.0308	40.11	0.0004
Peleg's model $Ct = \frac{t}{(k_1 + k_2 t)}$	90	k_1 = 0.0525	k_2 = 1.7755	98.64	0.0004
	150	k_1 = 0.0239	k_2 = 1.8210	98.19	0.0005
	300	k_1 = 0.0140	k_2 = 1.8495	98.92	0.0003
	600	k_1 = 0.0037	k_2 = 1.9222	99.88	<0.0001
	800	k_1 = 0.0055	k_2 = 1.9204	99.44	0.0001

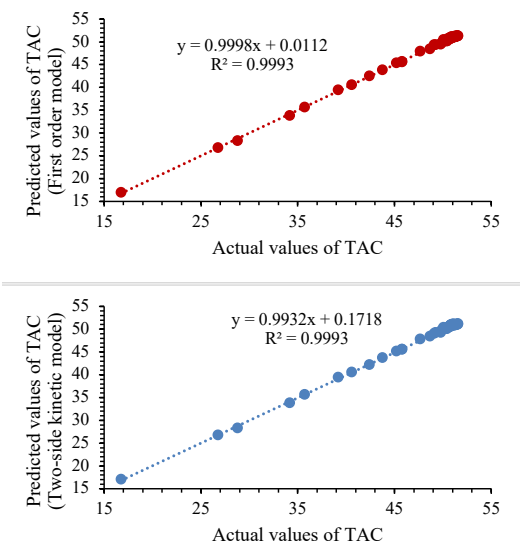

Figure 4. Regression analysis between experiment values and predicted values of TAC at different extraction conditions by selected models

The anthocyanin kinetic results indicate that the first-order model effectively describes the process, highlighting the significance of the rapid initial extraction phase during microwave application. Pavlić et al. (2023) reported superior first-order kinetics for the MAE of polyphenols. Additionally, Dong *et al*. (2014) observed the biphasic nature of MAE extraction kinetics, characterized by a fast phase followed by a slow phase, requiring a two-level model for comprehensive explanation. This indicates a resemblance in the kinetic mechanism of anthocyanin extraction from purple rice bran and other phenolic-rich plant materials when subjected to microwave treatment.

Conclusions

This study demonstrated the effectiveness of microwave-assisted extraction (MAE) using natural

deep eutectic solvents (NADES) for recovering bioactive compounds from pigmented "Cẩm" rice bran. The experimental results revealed that both total phenolic content (TPC) and anthocyanins exhibited a rapid release phase during the initial extraction period, followed by a plateau as equilibrium was approached. Optimal recovery was achieved within 5-10 minutes at moderate to high microwave power, indicating that MAE significantly reduced extraction time compared with conventional methods. Kinetic modeling confirmed that the extraction process was best described by the first-order and two-side kinetic models, both of which achieved excellent predictive accuracy ($R^2 > 0.99$). These models highlighted the dual nature of the extraction process, involving an initial fast release of easily accessible compounds followed by a slower diffusion-controlled phase. The findings also emphasized the synergistic role of NADES in enhancing solubility, stabilizing anthocyanins, and facilitating microwave energy absorption, thus contributing to higher yields in a sustainable manner. However, excessively high microwave power led to slight degradation of anthocyanins, underscoring the need for careful optimization of extraction parameters. By integrating MAE with green solvents, it not only advances sustainable extraction technologies but also contributes to the development of functional foods and nutraceuticals. Future research should focus on scale-up studies, techno-economic evaluation, and the stability of anthocyanins in formulated products to facilitate industrial applications.

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