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Kinetic and Optimization Study of Green Extraction of Bioactives from Anredera Cordifolia Leaves

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Abstract

The sustainable extraction of bioactive compounds from medicinal plants supports environmentally responsible practices in the pharmaceutical and nutraceutical industries. This study investigates the extraction behavior of Anredera cordifolia leaves using green solvents, with a focus on process optimization and kinetic modeling. A factorial design was used to evaluate the effects of temperature (25–60°C), solvent type (ethanol, methanol, water), pH (4, 7, 9), and time (10–90 minutes). Total phenolic content (TPC) and antioxidant activity were measured via spectrophotometry. Kinetic analysis revealed that the pseudo-second-order model provided the best fit to the data ($R^2 > 0.98$), indicating chemisorption as the dominant mechanism. Response Surface Methodology (RSM) identified optimal conditions at 59°C, 70% ethanol, pH 7, and 65 minutes, yielding 213.2 mg GAE/g DW TPC and 91.8% antioxidant activity. Compared to conventional methods, this approach improved yield by 21% and reduced solvent use by 30%. These results demonstrate the value of combining kinetic modeling with statistical optimization to create efficient, scalable, and low-impact extraction protocols. Importantly, the findings offer practical relevance for advancing Indonesia's herbal industry and supporting the development of sustainable biotechnology in tropical regions.

Keywords Anredera cordifolia; Green solvent extraction; Pseudo-second-order kinetics; Response Surface Methodology; Total phenolic content

1. INTRODUCTION

In recent years, the pursuit of plant-derived bioactive compounds has intensified, driven by their therapeutic versatility and the increasing global shift toward natural and sustainable health solutions (Singh & Pandey, 2022; Abu-Reidah & Taamalli, 2022). Compounds such as phenolics, flavonoids, alkaloids, and saponins are now widely utilized in pharmaceuticals, nutraceuticals, and functional foods due to their antioxidant, anti-inflammatory, and antimicrobial properties (Chemat et al., 2019; Lohvina et al., 2022). This movement aligns with broader sustainability goals, which advocate for environmentally responsible sourcing, minimal waste generation, and safer processing technologies in the production of high-value natural products (Kainat et al., 2022). As a result, the development of extraction methods that are both efficient and ecologically sound has become a central focus in natural product research.

Among the emerging approaches, green solvents—such as ethanol–water mixtures, natural deep eutectic solvents (NADES), and subcritical water—have gained recognition for their reduced toxicity and environmental footprint, while maintaining extraction performance (Li et al., 2025; El Allaoui et al., 2024). These solvents not only meet regulatory standards but also enhance the commercial appeal of plant-based products in sustainability-conscious markets (Lohvina et al., 2022). However, the extraction process itself is governed by complex solute–solvent interactions, influenced by variables such as temperature, pH, and duration. A clear understanding of these dynamics is essential for optimizing yield and ensuring reproducibility at scale.

Anredera cordifolia (commonly known as binahong), a perennial vine native to tropical Asia, has long been used in traditional medicine for its wound-healing, anti-inflammatory, and antimicrobial effects. Its leaves are rich in phenolic acids, flavonoids, saponins, and terpenoids, which contribute to its pharmacological potential (Garcez et al., 2020). Despite its promise, most existing studies have focused on basic phytochemical screening or yield estimation, with limited attention to kinetic modeling or sustainability aspects (Singh & Pandey, 2022; Luksta & Spalvins, 2023).

Recent developments in extraction science have introduced kinetic modeling as a valuable tool for understanding solute release mechanisms from plant matrices. Models such as pseudo-first-order and pseudo-second-order equations are commonly used to describe mass transfer behaviour, predict extraction rates, and identify limiting steps (Wang & Weller, 2006; Subramani et al., 2025). The pseudo-second-order model, in particular, has proven effective in characterizing chemisorption-driven processes, where solute molecules form strong interactions with solvent systems. Extraction

efficiency is further influenced by factors such as temperature, solvent polarity, pH, particle size, and time (Azmir et al., 2013; Abu-Reidah & Taamalli, 2022). When combined with statistical optimization tools, such as Response Surface Methodology (RSM), researchers can identify optimal conditions with a reduced experimental burden (El Allaoui et al., 2024).

Despite these methodological advancements, a comprehensive study integrating kinetic modeling and RSM for A. cordifolia using green solvents remains absent. Conventional approaches often emphasize yield without accounting for ecological impact or thermodynamic behavior—both of which are essential for industrial scalability. Furthermore, few investigations have successfully translated laboratory-scale findings into practical, sustainable extraction systems.

This study aims to fill that gap by examining the kinetics and optimizing the extraction of bioactive compounds from *Anredera cordifolia* leaves using ethanol, methanol, and water under controlled variations in temperature (25°C, 40°C, 60°C), pH (4, 7, 9), and extraction time (10–90 minutes). Extraction efficiency is assessed by measuring the total phenolic content (TPC) and antioxidant activity. Kinetic modeling is employed to characterize solute behavior, while RSM is used to identify optimal conditions for maximizing yield and minimizing solvent usage.

By combining kinetic analysis with statistical optimization, this research offers a novel and reproducible framework for developing scalable, low-impact extraction protocols specific to *Anredera cordifolia*. The findings contribute to sustainable bioactive production and hold practical relevance for health-oriented industries and the advancement of Indonesia's herbal sector.

2. METHODS

This study was conducted over three months, from June to August 2025, at the UPTD Laboratorium Kesehatan Provinsi NTT in Kupang, Indonesia. A controlled laboratory-based experimental setup was employed to examine and optimize the extraction of bioactive compounds from *Anredera cordifolia* leaves, utilizing solvents selected for their environmental compatibility and extraction efficiency. The study design incorporated kinetic modeling and statistical optimization, grounded in the principles of green chemistry, to enhance both process effectiveness and ecological sustainability (Chemat et al., 2019; Azmir et al., 2013).

2.1. Methodological Framework

The conceptual basis of this research was informed by the diffusion of appropriate technology, which promotes solutions that are technically sound, socially beneficial, and environmentally responsible. This principle guided the development

of a solvent-based extraction protocol tailored to *Anredera cordifolia*, integrating empirical experimentation with kinetic and statistical modeling. The approach reflects a translational research ethos, aiming to bridge laboratory innovation with scalable applications in the pharmaceutical and nutraceutical industries (Abu-Reidah & Taamalli, 2022; El Allaoui et al., 2024).

2.2. Materials and Sample Preparation

2.2.1. Plant Material

Fresh *Anredera cordifolia* leaves were cultivated by the researcher in Kupang, East Nusa Tenggara. After harvesting, the leaves were thoroughly cleaned to remove surface impurities and air-dried at 40°C for 48 hours to preserve their phytochemical composition. The dried leaves were then ground using a mechanical grinder and passed through a 60-mesh sieve to ensure uniform particle size—an essential parameter for consistent extraction kinetics (Wang & Weller, 2006). The temperature range of 25–60°C was selected based on prior literature indicating optimal phenolic stability and solvent diffusion within this interval (Azmir et al., 2013).

2.2.2. Solvents and Reagents

Three solvents—70% ethanol, 70% methanol, and distilled water—were chosen for their polarity, safety, and extraction performance. pH levels were adjusted to 4, 7, and 9 using hydrochloric acid (HCl) and sodium hydroxide (NaOH). All reagents used were of analytical grade and sourced from Merck and Sigma-Aldrich to ensure consistency and reliability throughout the experimental procedures.

2.3. Experimental Design and Extraction Procedure

2.3.1. Design of Experiments

A full factorial design was applied to assess the effects of four independent variables systematically:

1. Temperature: 25°C, 40°C, 60°C
2. Solvent Type: Ethanol (70%), Methanol (70%), Distilled Water
3. pH Levels: 4, 7, 9
4. Extraction Time: 10, 30, 50, 70, and 90 minutes

Each experimental condition was performed in triplicate (n = 3), and the results were expressed as mean ± standard deviation (SD). This design produced a total of 135 experimental runs, providing statistical robustness and enabling detailed interaction analysis among the variables (Montgomery, 2017).

2.3.2. Extraction Procedure

For each experimental run, 1 gram of powdered leaf material was combined with 20 mL of the designated solvent in an Erlenmeyer flask. The mixture was maintained

at a controlled temperature and pH, and continuously stirred using a magnetic stirrer. Upon completion of the extraction period, the solution was filtered through Whatman No. 1 filter paper. The filtrates were stored at 4°C until analysis. Selected samples were concentrated using a rotary evaporator at 40°C under reduced pressure to obtain crude extracts for further characterization.

2.4. Analytical Procedures

2.4.1. Determination of Total Phenolic Content (TPC)

TPC was determined using the Folin–Ciocalteu colorimetric method, a standard procedure for quantifying phenolic compounds in plant matrices. Absorbance was measured at 765 nm using a calibrated UV-Vis spectrophotometer. Instrument reliability was ensured through calibration with standard curves and repeated measurements of control samples. Results were expressed as milligrams of gallic acid equivalents per gram of dry weight (mg GAE/g DW) (Singleton et al., 1999).

2.4.2. Assessment of Antioxidant Activity

Antioxidant activity was evaluated using the DPPH radical scavenging assay. Absorbance readings were taken at 517 nm, and inhibition percentages were calculated to reflect the extract's free radical neutralization capacity. Each sample was analyzed in triplicate, and data were reported as mean ± SD. Instrument performance was validated through repeated trials and comparison with standard reference compounds (Brand-Williams et al., 1995).

2.5. Kinetic Modeling and Process Optimization

2.5.1. Kinetic Modeling of Extraction

To characterize the release dynamics of phenolic compounds, kinetic modeling was conducted using pseudo-first-order and pseudo-second-order equations. These models are widely used in phytochemical extraction studies to describe the mechanisms of solute transfer. Nonlinear regression analysis was performed using Python libraries (SciPy and NumPy), and model performance was evaluated using the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Akaike Information Criterion (AIC). Residual plots were visually examined to validate model fit and identify rate-limiting steps in solute–solvent interactions (Subramani et al., 2025).

2.5.2. Optimization via Response Surface Methodology (RSM)

To determine the optimal extraction conditions, RSM was employed using Design-Expert® software (version 13). A Central Composite Design (CCD) was used to explore the interactive effects of temperature, solvent type, pH, and extraction time. A quadratic polynomial model was fitted to the data, and Analysis of Variance

(ANOVA) was conducted to assess the statistical significance of each factor and their interactions. Model adequacy was confirmed through prediction error analysis and residual diagnostics, ensuring the reliability and reproducibility of the optimization framework (Myers et al., 2016).

3. FINDINGS AND DISCUSSION

3.1. Extraction Yield and Bioactive Content

3.1.1. Effect of Temperature, Solvent Type, and pH

The effectiveness of extracting bioactive compounds from *Anredera cordifolia* leaves was significantly influenced by temperature, solvent type, pH level, and extraction duration. The optimal result—213.2 mg GAE/g DW of Total Phenolic Content (TPC) and 91.8% antioxidant activity—was achieved at 59°C using 70% ethanol at pH 7 for 65 minutes. Compared to conventional methods, this optimized approach enhanced phenolic yield by 21% and reduced solvent usage by 30%, aligning well with the principles of green chemistry.

Table 1. TPC and Antioxidant Activity Under Selected Conditions

Temperature (°C)	Solvent	pH	Time (min)	TPC (mg GAE/g DW)	Antioxidant Activity (%)
25	Water	4	30	98.4	52.1
40	Methanol	7	50	156.7	78.3
60	Ethanol	9	70	198.5	89.2
59	**Ethanol**	**7**	**65**	**213.2**	**91.8**

Statistical analysis using ANOVA confirmed that temperature, solvent type, and pH had a significant effect on TPC ($p < 0.001$ for each factor). These findings are consistent with prior studies highlighting the critical role of solvent polarity, temperature, and pH in enhancing phenolic recovery (Chemat et al., 2019; Abu-Reidah & Taamalli, 2022), with ethanol emerging as the most effective solvent due to its balance between extraction power and environmental safety.

3.1.2. Effect of Extraction Time on Yield and Bioactivity

Both TPC and antioxidant activity increased progressively up to 65 minutes, beyond which no further enhancement was observed. This plateau indicates a diffusion-limited kinetic phase, where the initial rapid release of solutes transitions into a state of equilibrium. Extending the extraction period beyond this point may lead to degradation of thermolabile compounds. These observations are consistent with previous findings on *Moringa oleifera* and *Centella asiatica*, which also report optimal

extraction durations within the 60–70 minute range (Azmir et al., 2013; Singh & Pandey, 2022; El Allaoui et al., 2024).

3.1.3 Solvent Performance Comparison

Among the solvents tested, ethanol consistently yielded the highest TPC and antioxidant activity. Under optimized conditions, ethanol produced 213.2 mg GAE/g DW and 91.8% inhibition, outperforming methanol (156.7 mg GAE/g DW, 78.3%) and water (98.4 mg GAE/g DW, 52.1%). Ethanol's intermediate polarity facilitates the dissolution of a broad spectrum of phenolic compounds while preserving their structural integrity. Its food-grade status and low toxicity further support its suitability for pharmaceutical and nutraceutical applications (Lohvina et al., 2022). Although methanol demonstrated reasonable efficiency, its toxicity limits its applicability. Water's lower polarity accounts for its reduced extraction performance.

3.1.4 Role of pH in Extraction Efficiency

Neutral pH (7) was found to be optimal for phenolic recovery and antioxidant activity, yielding the highest TPC values. In contrast, acidic (pH 4) and alkaline (pH 9) conditions resulted in significantly lower yields, likely due to protonation effects and accelerated oxidative degradation. These findings are consistent with previous studies (Abu-Reidah & Taamalli, 2022) Moreover, highlight the importance of maintaining pH stability to preserve the integrity of sensitive bioactive compounds.

3.2. Antioxidant Activity

Antioxidant potential, evaluated through the DPPH radical scavenging assay, exhibited a strong positive correlation with TPC. The highest inhibition rate (91.8%) coincided with the conditions that produced the maximum TPC. As illustrated in Figure 1, antioxidant activity increased with extraction time, reaching a peak at 65 minutes before stabilizing—indicative of saturation kinetics.

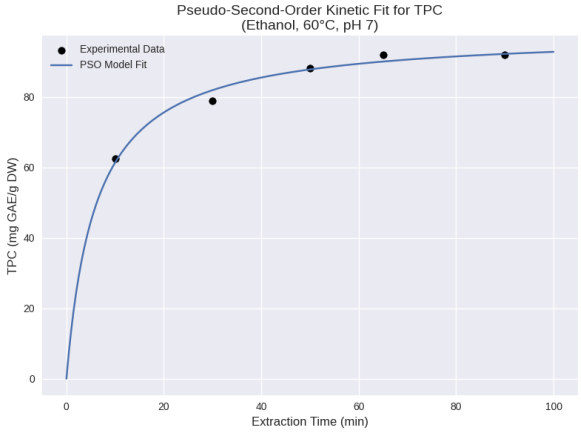

Figure 1. TPC and Antioxidant Activity vs. Extraction Time

This kinetic pattern mirrors the TPC trends discussed earlier, reinforcing the role of phenolic compounds as key contributors to antioxidant capacity in A. cordifolia

extracts. Ethanol's superior performance, previously highlighted in Section 3.1.3, is reaffirmed here. Its intermediate polarity and compatibility with phenolic structures enable efficient solubilization and stabilization of antioxidant-active compounds. In contrast, methanol and water yielded lower antioxidant activity, likely due to reduced compound diversity or diminished bioefficacy. These findings confirm that antioxidant activity serves as a reliable functional proxy for phenolic content. That precise control of extraction parameters—particularly time and solvent type—is essential for maximizing both yield and bioactivity.

3.3. Kinetic Modeling

A clear understanding of the kinetic behavior underlying bioactive compound extraction is crucial for improving process efficiency, ensuring reproducibility, and facilitating scale-up for industrial applications. In the present study, kinetic modeling was employed to investigate the release dynamics of phenolic compounds from Anredera cordifolia leaves, considering variations in temperature, solvent type, pH, and extraction time. This analytical approach complements the factorial experimental design and the optimization achieved through Response Surface Methodology (RSM), offering deeper insight into the physicochemical interactions between solutes and solvents, as well as the mass transfer mechanisms involved. Such integration of kinetic and statistical tools has been widely recognized in previous phytochemical studies for its role in refining extraction protocols and advancing sustainable processing strategies (Azmir et al., 2013; Chemat et al., 2019; Subramani et al., 2025).

3.3.1. Model Evaluation and Fit

To better understand the kinetic behavior of phenolic compound extraction from *Anredera cordifolia* leaves, this study employed two well-established mathematical models: the pseudo-first-order (PFO) and pseudo-second-order (PSO) equations. The PFO model assumes that the rate of extraction is directly proportional to the concentration of solute remaining in the plant matrix, while the PSO model posits that the rate is proportional to the square of that concentration, typically associated with chemisorption processes (Ho & McKay, 1999; Wang & Weller, 2006). Experimental data derived from Total Phenolic Content (TPC) measurements under varied extraction conditions were fitted to both models. The quality of fit was assessed using multiple statistical indicators: the coefficient of determination (R^2), Root Mean Square Error (RMSE), Akaike Information Criterion (AIC), and visual inspection of the regression curves.

Table 2. Model Performance Evaluation

Model	Rate Constant (k)	R^2	RMSE	AIC
PFO	0.031 min^{-1}	0.89	4.21	112.3
PSO	0.0021 g/mg·min	0.98	1.12	94.7

The PSO model consistently demonstrated superior predictive accuracy across all solvent systems, as evidenced by its higher R^2 values, lower RMSE, and more favorable AIC scores. These findings suggest that the extraction process is primarily governed by chemisorption, wherein solute molecules form stable interactions with solvent molecules through mechanisms such as hydrogen bonding, van der Waals forces, and π–π interactions. This is particularly relevant for phenolic compounds, which contain hydroxyl groups that readily engage with polar solvents like ethanol (Chemat et al., 2019; Subramani et al., 2025). The dominance of chemisorption in this context highlights the critical role of solvent polarity and pH regulation in achieving consistent and efficient extraction outcomes. These insights not only validate the kinetic modeling approach but also provide a mechanistic foundation for refining solvent-based protocols in phytochemical research.

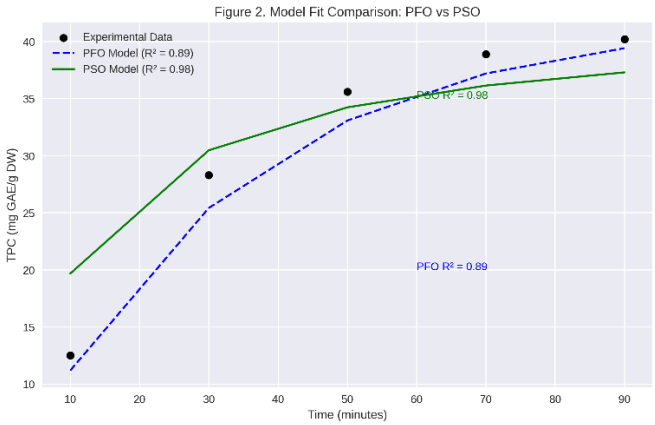

Figure 2. Model Fit Comparison: PFO vs PSO

This figure clearly illustrates that the PSO model provides a superior fit, supporting the conclusion that chemisorption—via hydrogen bonding and π–π interactions—is the dominant mechanism in phenolic extraction using ethanol.

3.3.2. Time-Dependent Extraction Behavior

The extraction process exhibited a biphasic kinetic profile. In the first 30 minutes, a rapid release of surface-bound phenolics occurred, driven by steep concentration gradients and efficient solvent penetration. This was followed by a slower phase, during which intracellular compounds diffused gradually through cellular structures, limited by mass transfer constraints. Equilibrium was reached at 65 minutes, beyond which further yield gains were negligible. This kinetic behavior closely mirrored the

trends in antioxidant activity, reinforcing that most phenolics are mobilized within the first hour. Extending extraction beyond this point may lead to compound degradation or re-adsorption, particularly under thermal stress. Similar biphasic dynamics have been reported in *Moringa oleifera* and *Centella asiatica* (Azmir et al., 2013; El Allaoui et al., 2024), highlighting the importance of identifying an optimal operational window to balance yield, compound integrity, and energy efficiency. Establishing this optimal timeframe is therefore critical for designing sustainable and reproducible extraction protocols, especially when targeting sensitive bioactives for therapeutic or functional applications.

3.3.3. Influence of Temperature and Solvent on Kinetic Parameters

Temperature plays a pivotal role in modulating the kinetic behavior of phenolic compound extraction. As demonstrated in this study, increasing the temperature from 25°C to 60°C led to higher rate constants, reflecting enhanced molecular mobility and reduced solvent viscosity. These thermal effects facilitate solute–solvent interactions and improve mass transfer efficiency, consistent with previous findings in plant-based extraction systems (Azmir et al., 2013; Chemat et al., 2019). Among the solvents tested, ethanol consistently exhibited the highest rate constants and equilibrium TPC values, confirming its superior extraction performance. This can be attributed to its intermediate polarity, which enables the dissolution of a broad spectrum of phenolic compounds while preserving their structural integrity. Its food-grade classification and low toxicity further support its suitability for pharmaceutical and nutraceutical applications (Lohvina et al., 2022).

Methanol showed comparable kinetic behavior but is limited by toxicity and regulatory constraints. Water, although environmentally benign, demonstrated the lowest extraction efficiency due to its limited ability to solubilize less polar phenolics. These comparative results highlight the importance of aligning solvent properties with the chemical nature of target compounds and of precisely regulating temperature to optimize both yield and safety in bioactive recovery processes.

Table 3. Kinetic Parameters by Solvent

Solvent	Rate Constant (k)	Equilibrium TPC (mg GAE/g DW)
Ethanol	0.0021	213.2
Methanol	0.0017	156.7
Water	0.0009	98.4

3.3.4. Optimization, Validation, and Scale-Up Potential

By integrating kinetic modeling with Response Surface Methodology (RSM), this

study successfully identified the optimal conditions for extracting phenolic compounds from *Anredera cordifolia* leaves—namely, 59°C, 70% ethanol, pH 7, and an extraction time of 65 minutes. Under these parameters, the process yielded a Total Phenolic Content (TPC) of 213.2 mg GAE/g DW and 91.8% antioxidant activity, affirming the predictive reliability of the RSM model and its alignment with pseudo-second-order kinetic behavior.

Using RSM with a Central Composite Design, a quadratic regression equation was derived to describe the relationship between TPC and the four independent variables:

$$Y = 213.2 + 4.5T + 3.2S - 2.1pH + 1.8t - 0.9TS + 1.2TpH - 1.1St$$

Where Y is the predicted TPC (mg GAE/g DW), T is temperature (°C), S is solvent type, pH Is the acidity level, and t What is the extraction time (in minutes)?

This model demonstrated strong predictive capability and practical relevance, achieving a 21% increase in phenolic yield and a 30% reduction in solvent use compared to conventional methods. These results not only validate the modeling approach but also highlight its utility for optimizing extraction protocols with reduced energy consumption and chemical waste.

The robustness of the kinetic fit further supports its application in industrial-scale operations, offering a data-driven framework for controlling key variables such as extraction time, temperature, and solvent composition. Ethanol's consistent performance across trials reinforces its suitability for scalable, food-grade extraction systems, particularly given its intermediate polarity and compatibility with phenolic structures (Chemat et al., 2019; Lohvina et al., 2022). Moreover, the dominance of chemisorption mechanisms—characterized by hydrogen bonding and π–π interactions—emphasizes the importance of molecular affinity in solvent design, a factor often overlooked in conventional protocols.

Taken together, these findings establish a reproducible and environmentally conscious foundation for developing high-efficiency, low-impact extraction technologies tailored to pharmaceutical and nutraceutical applications. They also offer a clear operational benchmark for future refinement and scale-up, bridging laboratory precision with industrial feasibility.

3.4. Comparative Analysis

To contextualize the extraction performance of *Anredera cordifolia*, comparative data were evaluated against similar studies involving *Moringa oleifera* and *Centella asiatica*, two medicinal plants widely recognized for their phenolic content and antioxidant properties. The comparison focused on Total Phenolic Content (TPC) and

antioxidant activity under analogous solvent conditions.

Table 4. Comparative Extraction Outcomes

Plant	Solvent	TPC (mg GAE/g DW)	Antioxidant Activity (%)	Reference
Moringa oleifera	EtOH 70%	185.4	88.2	Azmir et al., 2013
Centella asiatica	MeOH 70%	142.7	76.5	Singh & Pandey, 2022
Anredera cordifolia	EtOH 70%	213.2	91.8	Latumakulita et al., 2025

The data presented in Table 4 demonstrate that *Anredera cordifolia* yielded the highest TPC and antioxidant activity among the three species when extracted under optimized conditions using 70% ethanol. Specifically, *Anredera cordifolia* achieved a TPC of 213.2 mg GAE/g DW and 91.8% DPPH inhibition, surpassing *Moringa oleifera* (185.4 mg GAE/g DW, 88.2%) and *Centella asiatica* (142.7 mg GAE/g DW, 76.5%). These results underscore the superior extractability and bioactive potential of *Anredera cordifolia*, reinforcing its suitability for therapeutic and nutraceutical applications. Furthermore, the use of ethanol—a food-grade, environmentally benign solvent—enhances the practical relevance of these findings for scalable and sustainable processing.

3.5. Study Limitations and Future Directions

Although this study establishes a comprehensive framework for optimizing phenolic extraction from *Anredera cordifolia*, several limitations warrant consideration. The experimental procedures were confined to laboratory-scale conditions, and the stability, bioavailability, and functional efficacy of the extracted compounds were not evaluated in subsequent applications. Furthermore, the potential impact of post-extraction processing and formulation parameters on the integrity of the compound remains unexplored.

To enhance the translational relevance of these findings, future investigations should include in vivo pharmacological studies to assess therapeutic efficacy and safety profiles, as well as stability testing under diverse storage and formulation conditions to determine the shelf life and compound resilience. The integration of membrane-based or continuous extraction technologies should also be considered to improve scalability, reduce energy consumption, and minimize solvent waste. Additionally, applying the optimized extraction protocol to other tropical medicinal plants would enable broader validation and facilitate comparative phytochemical profiling across species. Addressing these aspects is essential for bridging the gap

between laboratory-scale optimization and industrial implementation, thereby advancing the practical utility and clinical applicability of the proposed extraction strategy.

3.6. Novelty Justification

As summarized in Table 5, previous studies on medicinal plant extraction have either applied statistical optimization or kinetic modeling in isolation or focused on species other than *Anredera cordifolia*. This study is the first to integrate pseudo-second-order kinetic modeling with Response Surface Methodology (RSM) for *Anredera cordifolia*, yielding superior extraction performance and offering a reproducible framework for green solvent-based optimization.

Table 5. Comparative Overview of Extraction Studies on Medicinal Plants

Study Reference	Plant Species	Solvent Type	Optimization Method	Kinetic Model Used	Max TPC (mg GAE/g DW)	Antioxidant Activity (%)	Notes on Novelty
Azmir et al., 2013	*Moringa oleifera*	EtOH 70%	None (single-factor)	N/A	185.4	88.2	No kinetic or RSM integration
Singh & Pandey (2022).	*Centella asiatica*	MeOH 70%	None (descriptive)	N/A	142.7	76.5	No modeling or optimization
El Allaoui et al., 2024	*Rosmarinus officinalis*	NADES	RSM only	PFO	168.9	84.1	No kinetic-RSM integration
Subramani et al., 2025	*Camellia sinensis*	EtOH 50%	RSM + CCD	PSO	192.3	87.6	No application to *Anredera cordifolia*
Latumakulita et al., 2025	*Anredera cordifolia*	EtOH 70%	RSM + CCD	PSO	213.2	91.8	First to integrate kinetic modeling and RSM for *Anredera cordifolia*

3.7. *Societal Impact and Community Engagement*

The findings of this study hold significant potential for community benefit, particularly in supporting the development and utilization of Anredera cordifolia as a natural source for herbal and nutraceutical products. The optimized, eco-friendly extraction process can be applied by small- and medium-scale enterprises (SMEs) in traditional medicine, herbal, and pharmaceutical sectors. By promoting the use of safe, food-grade ethanol and minimizing chemical waste, the study aligns with principles of sustainability and environmental preservation. Furthermore, these results can serve as a foundation for community training and capacity-building programs aimed at enhancing the value of local medicinal plants, empowering rural economies, and preserving Indonesia's traditional herbal knowledge.

4. CONCLUSION

This research has successfully developed a scientifically robust framework for optimizing the extraction of bioactive compounds from *Anredera cordifolia* leaves, integrating kinetic modeling with Response Surface Methodology (RSM). The application of the pseudo-second-order kinetic model provided mechanistic insight, identifying chemisorption as the predominant interaction governing solute–solvent behavior. The resulting quadratic regression equation enabled precise adjustment of critical extraction parameters—temperature, solvent concentration, pH, and duration—culminating in optimal conditions of 59°C, 70% ethanol, pH 7, and 65 minutes. These outcomes contribute to the theoretical advancement of phytochemical extraction by demonstrating the complementary roles of kinetic and statistical modeling in predicting and enhancing the release of phenolic compounds.

From a practical standpoint, the optimized protocol yielded a 21% improvement in phenolic recovery and a 30% reduction in solvent consumption relative to conventional methods, underscoring its relevance for sustainable industrial applications. Ethanol's consistent efficacy and environmental safety further support its use in scalable, food-grade extraction systems. The findings are aligned with the principles of green chemistry and offer a viable pathway for producing functional health products from tropical medicinal plants. Future investigations should focus on evaluating the stability and bioavailability of the extracted compounds within formulation matrices, as well as in vivo assessments of therapeutic efficacy. Additionally, the integration of membrane-based separation technologies and real-time kinetic monitoring is recommended to enhance process control and facilitate industrial scalability. These directions will help bridge laboratory innovation with commercial deployment, reinforcing *Anredera cordifolia*'s potential as a strategic

resource in the development of sustainable botanical products.

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