

7Biorefinery of Schisandra chinensis Vine Waste: An Integrated Green Process Coupling Deep Eutectic Solvent Extraction with Electrodialysis for Lignan Recovery

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Abstract

Purpose: This study aimed to develop a green and sustainable integrated biorefinery process for the valorization of *Schisandra chinensis* vine waste biomass by coupling deep eutectic solvent (DES) extraction with electrodialysis for lignan recovery.

Methods: A glycine–lactic acid (1:3 molar ratio) DES was employed for ultrasonic-assisted extraction of lignans from *S. chinensis* vine stems, with a water pretreatment step to enhance efficiency. Key parameters were screened by Plackett–Burman design and optimized by Box–Behnken response surface methodology. A three-compartment electrodialysis system was used for DES recovery. Antioxidant activity was evaluated by DPPH and ABTS assays.

Results: The water pretreatment–DES two-step method significantly outperformed ethanol extraction (2.5-fold) and single-step DES extraction (1.6-fold). Optimal conditions were: ultrasonic time 40 min, temperature 40 °C, solid–liquid ratio 1:20 g·mL⁻¹.

Conclusion: This integrated process provides a scalable, sustainable biorefinery strategy for converting *S. chinensis* vine waste biomass into high-value lignan products, aligning with circular bioeconomy and green biomass processing principles.

Introduction

Schisandra chinensis (Turcz.) Baill., a well-known medicinal and edible plant of the Schisandraceae family, produces fruits that are extensively utilized in functional foods, nutraceuticals, health products, and natural flavorings [1, 2]. However, the stems and vines—the primary by-products of fruit harvesting and processing—are routinely discarded as agricultural waste, leading to the loss of valuable bioactive resources and contributing to environmental burden [3]. These stems possess a characteristic natural aroma enabling direct application as a sustainable spice without additional flavoring agents [4], and are rich in bioactive dibenzocyclooctadiene lignans including schisandrol A, schisandrol B, schisandrin A, schisandrin B, and schisandrin C, which exhibit sedative, sleep-promoting, hepatoprotective, and antioxidant properties [5–7]. Therefore, *S. chinensis* vine waste represents an excellent yet underutilized lignocellulosic biomass resource, and its high-value valorization through biorefinery approaches holds considerable economic and ecological significance.

Efficient extraction is the critical first step for recovering lignans from plant matrices. Conventional ethanol or water extraction methods suffer from inherent limitations: water exhibits low efficiency due to the hydrophobic nature of lignans, while ethanol raises concerns regarding residual organic solvents and food safety. These shortcomings restrict industrial translation [8]. Consequently, there is an urgent need for efficient, green, and sustainable biomass extraction technologies.

Deep eutectic solvents (DES) have emerged as promising green solvents characterized by low toxicity, favorable biodegradability, ease of preparation, and low cost [9]. DES formulated from low-toxicity,

biodegradable components are especially attractive for biomass valorization and biorefinery applications. Recent studies have demonstrated their effectiveness in recovering bioactive compounds from food industry by-products, including anthocyanins from red radicchio [10], phenolics from citrus peel [11], and polyphenols from brewer's spent grain [12,13]. Glycine, a natural amino acid with established food safety [14], and lactic acid, a common food preservative and acidulant [15], are both food-grade raw materials that can form a DES through hydrogen-bond interactions. The glycine–lactic acid DES system is environmentally benign, exhibits excellent solubilizing capacity for hydrophobic lignans through multiple hydrogen-bonding mechanisms, and eliminates the risks associated with conventional organic solvents, providing a green route to produce high-purity extracts suitable for incorporation into high-value nutraceutical and functional products.

Nevertheless, residual DES components in the final extract can compromise product purity and interfere with downstream application characteristics. Electrodialysis is a mild, green membrane separation technology that selectively transports ionic components across ion-exchange membranes under an applied electric field without requiring additional organic solvents, offering operational simplicity, low energy consumption, and the absence of secondary pollution [16,17]. To date, no study has reported the combined use of glycine–lactic acid DES for lignan extraction from *S. chinensis* stems with electrodialysis for DES removal and recovery, nor has a systematic comparison with conventional extraction methods been conducted.

In the present study, discarded *S. chinensis* stems were utilized as raw material, and glycine–lactic acid DES was employed for lignan extraction, with conventional ethanol and water extractions serving as controls. Electrodialysis was optimized to remove and recover DES while retaining target lignans. The specific objectives were to: (i) systematically screen and optimize DES composition and extraction parameters using statistical experimental designs; (ii) evaluate the synergism of water pretreatment combined with DES extraction; (iii) assess the feasibility of electrodialysis for DES recovery and solvent reuse; and (iv) characterize the antioxidant activity of the resulting lignan extract. This integrated “green extraction–efficient recovery” process aims to enable the high-value utilization of *S. chinensis* stem waste and provide scientific support for the application of DES in sustainable biomass processing and biorefinery.

Materials and Methods

Materials and Reagents

The stem samples of *Schisandra chinensis* (Turcz.) Baill. were collected from the Suiyennongye Chinese Herbal Medicine Demonstration Base in Sifengshan, Jiamusi City, Heilongjiang Province, China. The plant material was authenticated as the vine stems of *S. chinensis* by Professor Wang Lihong of the School of Pharmacy, Jiamusi University. A voucher specimen was deposited at the herbarium of the School of Pharmacy, Jiamusi University. The dried stems were pulverized using a laboratory grinder, passed through a 40-mesh sieve (425 μm), and stored in a desiccator at room temperature until use.

Choline chloride ($\geq 98\%$), alanine ($\geq 99\%$), proline ($\geq 99\%$), glycine ($\geq 99\%$), citric acid ($\geq 99.5\%$), malic acid ($\geq 99\%$), L-lactic acid ($\geq 85\%$, food-grade), levulinic acid ($\geq 98\%$), and reference standards of schisandrol A, schisandrol B, schisandrin A, schisandrin B, and schisandrin C (all $\geq 98\%$ purity, HPLC-grade) were purchased from Shanghai Yuanye Bio-Technology Co., Ltd. (Shanghai, China). Oxalic acid ($\geq 99.5\%$) was obtained from Liaoning Quanrui Reagent Co., Ltd. (Liaoning, China). Formic acid (LC-MS grade), acetonitrile (HPLC grade), and methanol (HPLC grade) were acquired from Thermo Fisher Scientific (Waltham, MA, USA). Deionized water (18.2 M Ω ·cm) was produced using a Master Touch-S15 laboratory ultrapure water system (Hitech Instruments Co., Ltd., Shanghai, China).

HPLC Analysis of Lignans

Quantitative determination of five marker lignans was performed using an Agilent 1260 HPLC system (Agilent Technologies, Santa Clara, CA, USA) equipped with a quaternary pump, autosampler, column thermostat, and diode array detector (DAD). Chromatographic separation was achieved on a Supersil ODS2 C18 column (4.6 mm $\times$ 250 mm, 5 μ m; Dalian Elite Analytical Instruments Co., Ltd., Dalian, China). The mobile phase consisted of acetonitrile (A) and 0.1% (v/v) aqueous phosphoric acid (B). The gradient program was: 0–12 min, 51% A; 12–30 min, 51% $\rightarrow$ 65% A (linear); 30–40 min, isocratic 65% A; 40–50 min, 65% $\rightarrow$ 100% A (linear). The column temperature was 30°C, flow rate 1.0 mL·min⁻¹.

UHPLC-HRMS Analysis of Glycine and Lactic Acid

Glycine and lactic acid were determined using a Dionex Ultimate 3000 UHPLC system coupled to a Q Exactive high-resolution mass spectrometer (Thermo Fisher Scientific, Waltham, MA, USA). Chromatographic separation was performed on a Thermo Scientific Hypersil GOLD C18 column (2.1 $\times$ 100 mm, 1.9 μ m) with a guard column (C18, 4.6 $\times$ 150 mm, 2.1 μ m). The mobile phase was 0.1% (v/v) formic acid in water (A) and methanol (B) (95:5, v/v, isocratic) at 0.3 mL·min⁻¹. The mass spectrometer was operated in full-scan mode over m/z 50–1500, cycle count 3, quadrupole isolation window 1.5 m/z, and dynamic exclusion 5 s. Quantification was performed by the external standard method.

Analytic Hierarchy Process (AHP) Weight Assignment

To comprehensively evaluate lignan extraction efficiency, the Analytic Hierarchy Process (AHP) was employed to assign objective weights to each target component. A pairwise comparison judgment matrix was constructed based on the relative pharmacological activities, clinical significance, and pharmacopoeial quality-control importance of the five lignans reported in the literature. The consistency ratio (CR) of the judgment matrix was verified to be < 0.10 , confirming acceptable consistency. The calculated weight coefficients for schisandrol A, schisandrol B, schisandrin A, schisandrin B, and schisandrin C were 41.62%, 26.18%, 16.11%, 9.86%, and 6.24%, respectively. The weighted

comprehensive score (Y) was calculated according to Eq. (1) and used as the response variable for all process optimization experiments:

$$Y = 0.4162 \times (CSA / CSA_{max}) + 0.2618 \times (CSB / CSB_{max}) + \dots + 0.0624 \times (CSC / CSC_{max}) \quad (1)$$

where C_i is the measured concentration of each lignan and $C_{i,max}$ is the maximum concentration of that lignan across all experiments.

Extraction Process Optimization

Screening of the Optimal DES System

Based on previous literature on DES-based extraction of natural products [18–22], seven DES systems with different hydrogen-bond acceptor (HBA)–hydrogen-bond donor (HBD) combinations were prepared at the following molar ratios: glycine–lactic acid (1:3), proline–lactic acid (1:1), proline–citric acid (1:1), alanine–citric acid (1:1), choline chloride–lactic acid (1:1), choline chloride–levulinic acid (2:3), and choline chloride–malic acid (1:1). Each mixture was stirred in a sealed vessel at 70°C until a homogeneous, transparent liquid formed (typically 30–60 min), confirming DES formation. For screening, 1.000 g of stem powder was extracted with each DES (20 mL) by ultrasonic-assisted extraction at 160 W and 40°C for 50 min. After centrifugation, the supernatant was collected, filtered through a 0.45-μm membrane, and analyzed by HPLC. All experiments were performed in triplicate.

Comparison of Water Pretreatment–DES Two-Step vs. Single-Step Extraction

To investigate the effect of water pretreatment on extraction efficiency, equal amounts of *S. chinensis* stem powder (1.000 g each) were divided into a control group and an experimental group ($n = 3$ per group). The control group was directly subjected to DES extraction under the conditions described above. For the experimental group, a water pretreatment step was performed: the stem powder was first extracted with deionized water (20 mL) by ultrasonication at 160 W and 40°C for 30 min. After centrifugation, the aqueous supernatant was discarded. The dried residue was then extracted using the same DES under identical conditions. Total lignan yields were determined by HPLC. Additionally, conventional 70% (v/v) ethanol extraction and water extraction (both at 1:20 solid–liquid ratio, 40°C, 50 min ultrasonication) were performed as reference methods.

Single-Factor Experiments

Seven key process parameters were investigated through single-factor experiments: solid–liquid ratio (A, 1:10–1:50 g·mL^{−1}), ultrasonic time (B), water content in DES (C, 0–50% v/v), ultrasonic power (D), soaking time (E), number of water pre-extraction cycles (F), and ultrasonic temperature (G). The

weighted comprehensive score based on the concentrations of schisandrol A, schisandrol B, schisandrin A, schisandrin B, and schisandrin C was used as the response variable. The detailed experimental design is shown in Table S1.

Plackett–Burman (PB) Screening Design

Based on the single-factor results, a Plackett–Burman screening design with 12 runs was employed using Design-Expert software (Version 8.0.6, Stat-Ease Inc., Minneapolis, MN, USA) to identify factors with statistically significant effects on lignan yield. Seven factors were evaluated at two levels (– 1 and + 1); factor levels are presented in Supplementary Table S2.

Box–Behnken Design (BBD) and Response Surface Optimization

Based on the PB screening results, three factors—ultrasonic time (A), ultrasonic temperature (B), and solid–liquid ratio (C)—were selected as independent variables for response surface optimization. A three-factor, three-level Box–Behnken design consisting of 17 experimental runs (including five center points) was constructed using Design-Expert 12 software. Factor levels are provided in Supplementary Table S3. Each run was performed in triplicate, and the weighted comprehensive score (Y) was used as the response. The data were fitted to a second-order polynomial regression model:

$$Y = \beta_0 + \sum \beta_i X_i + \sum \beta_{ii} X_i^2 + \sum \sum \beta_{ij} X_i X_j \quad (2)$$

DES Recovery by Electrodialysis

DES component recovery was performed using a laboratory-scale three-compartment electrodialysis cell equipped with one anion-exchange membrane (AEM) and one cation-exchange membrane (CEM), each with an effective area of 30 cm². The DES extract obtained under optimal conditions was diluted 1.5-fold with deionized water and introduced into the middle (feed) compartment. Both electrode compartments were initially filled with 0.1 mol·L^{–1} oxalic acid solution as the electrode rinse

Electrodialysis was conducted at a constant voltage of 25 V (DC) at ambient temperature (25 ± 2°C). Under the applied electric field, lactate anions migrated across the AEM toward the anode compartment, while glycine (present as glycinium cations under the acidic conditions provided by oxalic acid) migrated across the CEM toward the cathode compartment. Electrically neutral lignan molecules remained in the middle compartment. Aliquots were collected from each compartment at predetermined intervals and analyzed by UHPLC-HRMS. The recovery rate of each DES component was calculated as the ratio of the mass recovered in the respective electrode compartment to the initial mass used in DES preparation.

To evaluate lignan retention, the concentrations of the five marker lignans in the middle compartment were determined by HPLC before and after electrodialysis. Furthermore, the glycine-rich and lactic acid-rich solutions recovered from the cathode and anode compartments were combined, and excess oxalic acid was removed by evaporation under reduced pressure. After concentration adjustment, glycine and

lactic acid were remixed at the initial molar ratio of 1:3 to reconstitute the DES. The regenerated DES was then tested for lignan extraction performance under optimized conditions, and yields of all five lignans were compared with those obtained using freshly prepared DES.

Antioxidant Activity Assays

DPPH Radical Scavenging Assay

The DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging activity was determined according to a previously described method [23] with minor modifications. Briefly, 100 μL of the extract solution at various concentrations (0.2, 0.4, 0.6, 0.8, and 1.0 $\text{mg}\cdot\text{mL}^{-1}$) were mixed with 100 μL of 0.1 $\text{mmol}\cdot\text{L}^{-1}$ DPPH ethanolic solution in 96-well plates. After incubation in the dark at room temperature for 30 min, the absorbance was measured at 517 nm using a microplate reader.

$$\text{DPPH scavenging rate (\%)} = [1 - (A1 - A2) / A0] \times 100\% \quad (3)$$

where $A0$ is the absorbance of the DPPH solution mixed with absolute ethanol (blank), $A1$ is the absorbance of the sample mixed with DPPH solution, and $A2$ is the absorbance of the sample mixed with absolute ethanol (sample blank). All measurements were performed in triplicate.

ABTS Radical Cation Scavenging Assay

The ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) radical cation scavenging activity was assessed according to a reported method [24] with slight modifications. The ABTS $^{\bullet+}$ stock solution was prepared by reacting 7 $\text{mmol}\cdot\text{L}^{-1}$ ABTS with 2.45 $\text{mmol}\cdot\text{L}^{-1}$ potassium persulfate in the dark at room temperature for 12–16 h. The working solution was diluted with phosphate-buffered saline (pH 7.4) to an absorbance of 0.70 ± 0.02 at 734 nm. Then, 100 μL of the extract solution at various concentrations (0.2, 0.4, 0.6, 0.8, and 1.0 $\text{mg}\cdot\text{mL}^{-1}$) was mixed with 100 μL of ABTS $^{\bullet+}$ working solution, incubated at room temperature for 6 min, and the absorbance was measured at 734 nm.

$$\text{ABTS}^{\bullet+} \text{ scavenging rate (\%)} = [1 - (A1 - A2) / A0] \times 100\% \quad (4)$$

where $A0$, $A1$, and $A2$ are defined analogously to the DPPH assay. All measurements were performed in triplicate.

Statistical Analysis

All experiments were performed in triplicate, and results are expressed as mean $\pm$ standard deviation (SD). Statistical analyses were conducted using Design-Expert software (Versions 8.0.6 and 12, Stat-Ease Inc.) for experimental design and response surface modeling, and SPSS Statistics (Version 26.0, IBM Corp., Armonk, NY, USA) for additional analyses. One-way analysis of variance (ANOVA) followed by Tukey's HSD post-hoc test was used to assess significant differences between groups, with $p < 0.05$ considered statistically significant. Model adequacy was evaluated through the coefficient of determination (R^2), adjusted R^2 , predicted R^2 , lack-of-fit test, and adequate precision.

Results

Method Validation and Lignan Standard Curves

The HPLC method for simultaneous determination of the five marker lignans was validated in terms of linearity, precision, accuracy, and sensitivity. Chromatographic separation of the five standards is illustrated in Fig. 1, demonstrating baseline resolution of all target analytes within 50 min. Five-point standard calibration curves were constructed by plotting peak area (y) against standard concentration (x). As summarized in Supplementary Table S4, the correlation coefficients (R^2) for all five lignans exceeded 0.999, confirming excellent linearity over the tested concentration ranges. The limits of detection (LOD, $S/N = 3$) and quantification (LOQ, $S/N = 10$) were determined for each analyte. Method precision (RSD) was below 3% for both intra-day and inter-day measurements, demonstrating satisfactory method performance.

Screening of the Optimal DES System

The extraction efficiency of lignans is strongly influenced by the physicochemical properties of the DES, which are determined by the nature and molar ratio of the HBA and HBD components. Among the seven DES systems evaluated (Fig. 2), the glycine–lactic acid DES (molar ratio 1:3) consistently exhibited the highest extraction yields for all five target lignans as well as the highest weighted comprehensive score. This superior performance can be attributed to several factors: (i) the strong hydrogen-bond accepting capacity of glycine combined with the hydrogen-bond donating ability of lactic acid creates a DES with high polarity and excellent solvation power; (ii) the carboxylic acid and amino groups in the DES can form multiple hydrogen bonds with the methoxy, hydroxyl, and dioxole functional groups present in dibenzocyclooctadiene lignans; and (iii) the relatively low viscosity at the 1:3 molar ratio facilitates mass transfer during ultrasonic extraction. In contrast, DES systems containing choline chloride as the HBA showed lower lignan extraction efficiency, possibly due to weaker specific interactions with the lignan scaffold. Consequently, the glycine–lactic acid (1:3) DES was selected as the optimal solvent system for all subsequent experiments.

Comparison of Extraction Methods

A comparative study was conducted to evaluate the extraction efficiency of four different methods: water extraction alone, DES extraction alone, water pretreatment followed by DES extraction (two-step

method), and conventional 70% ethanol extraction. As shown in Table 1, the two-step water pretreatment–DES method yielded significantly higher amounts of all five lignans compared with all other methods ($p < 0.05$). The total lignan yield from the two-step method was approximately 1.6-fold higher than that of single-step DES extraction, 2.5-fold higher than ethanol extraction, and 3.5-fold higher than water extraction.

This remarkable enhancement is attributed to a synergistic mechanism: the initial water pretreatment effectively disrupts the plant cell wall matrix through hydration and swelling, removes water-soluble interfering compounds (e.g., free sugars, organic acids, and polar proteins), and loosens the lignocellulosic structure. This increases the porosity and permeability of the plant material, thereby reducing mass transfer resistance and facilitating subsequent DES penetration into the cellular matrix. Once inside, the DES maximizes its advantages in hydrogen-bonding interactions and targeted dissolution of the hydrophobic lignans.

Table 1
Comparison of lignan yields obtained by different extraction methods (mg·g⁻¹ n = 3)

Lignan	Water extraction	DES extraction	Water + DES	Ethanol extraction
Schisandrol A	1.34 ± 0.08	1.66 ± 0.10	2.64 ± 0.12	2.15 ± 0.11
Schisandrol B	0.81 ± 0.05	1.58 ± 0.09	2.41 ± 0.13	1.93 ± 0.10
Schisandrin A	0.13 ± 0.02	0.36 ± 0.03	0.69 ± 0.04	0.40 ± 0.03
Schisandrin B	0.24 ± 0.02	0.83 ± 0.05	0.95 ± 0.06	1.08 ± 0.06
Schisandrin C	0.04 ± 0.01	0.10 ± 0.01	0.18 ± 0.02	0.15 ± 0.01

Single-Factor Experimental Analysis

The effects of the seven individual process parameters on the weighted comprehensive score are presented in Fig. 3. All factors exhibited a characteristic trend where the response initially increased, reached a maximum, and then either decreased or plateaued at higher levels. Specifically: (i) lignan yield increased with increasing water content up to 25% (v/v) and then declined, consistent with the fact that a moderate water content reduces DES viscosity and enhances mass transfer, whereas excessive water disrupts the DES hydrogen-bond network; (ii) two cycles of water pre-extraction were optimal, with additional cycles offering no further improvement; (iii) the optimal solid–liquid ratio was 1:20 g·mL⁻¹.

Plackett–Burman Screening Design

The PB design matrix and experimental results are presented in Supplementary Table S5 The first-order regression equation obtained was:

$$Y = 72.18 + 0.1667A + 1.98B + 7.85C + 8.55D + 1.62E + 7.07F + 0.55G$$

The model R^2 of 0.9753 indicated an excellent fit. ANOVA (Supplementary Table S6) revealed that the model was highly significant ($p = 0.0069$). Among the seven factors, ultrasonic time (C), ultrasonic temperature (D), and solid–liquid ratio (F) were the most influential parameters, each exhibiting a highly significant effect on lignan yield ($p < 0.01$). The adjusted R^2 of 0.9166 indicated that the model explained 91.66% of the total response variation. The three significant factors were advanced to the response surface optimization stage, while non-significant factors were fixed at their optimal levels.

Box–Behnken Design and Response Surface Optimization

The 17-run Box–Behnken design matrix and corresponding comprehensive scores are detailed in Supplementary Table S7. Multiple regression analysis yielded the following second-order polynomial equation (in coded factors):

$$Y = 86.63 + 3.02A + 2.61B - 0.4850C - 3.68AB - 3.40AC - 0.7825BC - 12.86A^2 - 11.62B^2 - 9.02C^2$$

The ANOVA results for the quadratic model are presented in Supplementary Table S8. The model was highly significant ($F = 34.25$, $p < 0.0001$), whereas the lack of fit was not significant ($F = 0.4673$, $p = 0.7210$), collectively confirming the excellent goodness of fit. The coefficient of determination $R^2 = 0.9778$, adjusted $R^2 = 0.9492$, predicted $R^2 = 0.9237$, and adequate precision of 18.74 (> 4) indicated an adequate signal-to-noise ratio.

All three linear terms (A, B, C) and all three quadratic terms (A^2 , B^2 , C^2) were statistically significant ($p < 0.05$), with the quadratic terms exerting the most pronounced effects as evidenced by their large negative coefficients. Among the interaction terms, AB and AC were significant ($p < 0.05$), whereas the BC interaction was not significant. The three-dimensional response surface plots and corresponding contour plots are presented in Fig. 4. The elliptical contours for the AB and AC interactions corroborated the significant interactions identified by ANOVA. Based on the magnitude of the linear coefficients and F-values, the relative influence followed the order: ultrasonic time (A) $>$ ultrasonic temperature (B) $>$ solid–liquid ratio (C). Numerical optimization using the desirability function approach yielded the following optimal conditions: ultrasonic time 40 min, ultrasonic temperature 40°C, and solid–liquid ratio 1:20 ($\text{g}\cdot\text{mL}^{-1}$). Under these conditions, the predicted comprehensive score was 86.63, and the experimental verification yielded a score of 85.92 ± 1.24 ($n = 3$), confirming the reliability and reproducibility of the optimized process.

DES Recovery by Electrodialysis and Solvent Reusability

The electrodialysis process successfully achieved the selective separation and recovery of glycine and L-lactic acid from the DES extract. As shown in Fig. 5, the recovery of both components followed a characteristic kinetic profile: rapid migration during the initial 40–60 min, followed by a gradual approach to equilibrium. The final recovery rates reached 92.97% for glycine and 86.98% for L-lactic acid after 120 min of operation. The slightly lower recovery of lactic acid compared with glycine may be attributed to

the larger molecular size and lower electrophoretic mobility of the lactate anion relative to the glycinium cation, as well as potential concentration polarization effects at the membrane surface.

The concentrations of the five target lignans in the middle compartment showed minimal changes before and after electrodialysis treatment (Table 2), confirming that the electrically neutral lignan molecules were effectively retained in the feed compartment. This selective retention is a key advantage of the electrodialysis approach.

Figure 5 Recovery rate curve

The glycine and lactic acid recovered from the respective electrode compartments were successfully recombined at the original 1:3 molar ratio to reconstitute the DES. The regenerated DES exhibited extraction performance comparable to that of freshly prepared DES (Table 2), with lignan yields reaching 93–94% of the original values for the major components.

Table 2
Lignan yields before electrodialysis, after electrodialysis, and using regenerated DES (mg·g⁻¹, n = 3)

Lignan	Before ED	After ED	Regenerated DES	Recovery (%)
Schisandrol A	3.12 ± 0.15	2.66 ± 0.13	2.89 ± 0.14	92.6
Schisandrol B	3.22 ± 0.16	2.71 ± 0.14	3.02 ± 0.15	93.8
Schisandrin A	0.81 ± 0.04	0.63 ± 0.03	0.68 ± 0.04	84.0
Schisandrin B	0.97 ± 0.05	0.62 ± 0.04	0.61 ± 0.03	62.9
Schisandrin C	0.36 ± 0.02	0.17 ± 0.02	0.25 ± 0.02	69.4

ED: electrodialysis. Recovery (%) = (regenerated DES yield / before ED yield) × 100%.

Antioxidant Activity of the Lignan Extract

The antioxidant potential of the lignan extract was evaluated using two complementary radical scavenging assays. As illustrated in Fig. 6, both DPPH and ABTS radical scavenging activities exhibited a clear concentration-dependent response within the tested range of 0.2–1.0 mg·mL⁻¹.

Discussion

The present study successfully established an integrated green process that combines water pretreatment, DES ultrasonic extraction, and electrodialysis-assisted solvent recovery for the valorization of *S. chinensis* vine waste. This integrated approach addresses three critical challenges in the field of biomass valorization: extraction efficiency, product quality, and process sustainability.

First, the superior extraction performance of the glycine–lactic acid DES over conventional solvents can be rationalized by its unique solvation mechanism. Unlike water or ethanol, which primarily interact with solutes through simple polarity-based interactions, DES engages in multiple and specific hydrogen-bonding interactions with lignan molecules. The glycine component provides both hydrogen-bond donor and acceptor sites, enabling strong and specific interactions with the methoxy, hydroxyl, and dioxole groups of lignan molecules. The water pretreatment further amplifies this effect by disrupting the plant cell wall architecture, consistent with the well-established principles of lignocellulosic biomass pretreatment in biorefinery operations. The resulting yields of the five marker lignans ($0.36\text{--}3.22\text{ mg}\cdot\text{g}^{-1}$) were obtained from vine stem waste—a biomass fraction with inherently lower lignan content than fruits. Although lower in absolute terms than those reported for fruit-based DES extractions [8, 21], these yields demonstrate the feasibility of efficiently valorizing an otherwise discarded agricultural residue through the proposed integrated biorefinery process.

Second, the systematic application of statistical experimental designs—PB screening followed by BBD response surface optimization—enabled the efficient identification of critical process parameters and their optimal levels with a minimal number of experimental runs. This statistically rigorous approach is essential for process development and scale-up, as it provides validated predictive models that account for both linear and interaction effects among variables. The excellent agreement between the predicted and experimental verification values confirms the robustness of the optimized conditions. The identification of ultrasonic time as the most influential factor, followed by ultrasonic temperature and solid–liquid ratio, is consistent with the mechanism of ultrasonic-assisted extraction, where cavitation effects and contact time are known to be the primary drivers of mass transfer enhancement.

Third, the successful integration of electrodialysis for DES recovery represents a significant advance toward process sustainability and economic viability. The high recovery rates ($> 86\%$) and the demonstrated reusability of the regenerated DES establish the technical feasibility of a closed-loop solvent cycle. Compared with alternative DES removal strategies such as solid-phase extraction, liquid–liquid extraction, or precipitation, electrodialysis offers the distinct advantages of being solvent-free, continuous-operable, and amenable to scale-up [25]. The concurrent retention of lignans in the feed compartment further simplifies the downstream processing, as the extract can be directly concentrated and formulated into high-value products without additional purification steps.

The lignan extract exhibited strong, concentration-dependent antioxidant activity in both DPPH and ABTS assays, which can be attributed to the structural features of dibenzocyclooctadiene lignans, particularly the multiple methoxy and hydroxyl groups capable of donating hydrogen atoms or electrons to stabilize free radicals. The relatively high purity achieved through the DES extraction–electrodialysis process likely contributes to this potent antioxidant activity by minimizing the dilution effect of co-extracted inactive impurities.

From a practical application standpoint, the resulting lignan extract—with substantially reduced DES content—represents a high-value product stream derived from agricultural biomass waste. The

recovered lignans, including schisandrol A, schisandrol B, schisandrin A, schisandrin B, and schisandrin C, possess well-documented bioactivities (antioxidant, hepatoprotective, and sedative properties) and can serve as value-added intermediates for the nutraceutical, pharmaceutical, and functional product industries. The valorization of vine waste, currently a low-value agricultural residue, into high-value lignan products aligns with circular bioeconomy principles and contributes to the sustainable development goals of biomass-based industries.

Nevertheless, several aspects warrant further investigation before industrial implementation: (i) pilot-scale validation of the integrated process to assess scalability and techno-economic feasibility; (ii) long-term stability studies of the lignan extract under various storage conditions; (iii) comprehensive compatibility evaluation of the extract with various product formulations; (iv) detailed life-cycle assessment to quantify the environmental footprint relative to conventional approaches; and (v) toxicological safety assessment of the final extract to support regulatory approval in various jurisdictions.

Conclusions

This study developed and validated a green, sustainable, and scalable integrated process for the valorization of *Schisandra chinensis* vine waste biomass into high-value lignan products. The principal findings are:

1. A glycine–lactic acid DES (molar ratio 1:3) was identified as the optimal green solvent for lignan extraction, significantly outperforming conventional water and ethanol extraction methods.
2. The water pretreatment–DES two-step extraction strategy demonstrated a synergistic effect, achieving 1.6-fold and 2.5-fold higher total lignan yields compared with single-step DES extraction and ethanol extraction, respectively.
3. Systematic optimization using Plackett–Burman screening and Box–Behnken response surface methodology identified the optimal extraction conditions (ultrasonic time: 40 min, temperature: 40°C, solid–liquid ratio: 1:20 g·mL⁻¹, $R^2 = 0.9778$).
4. Electrodialysis enabled efficient DES recovery (glycine: 92.97%, L-lactic acid: 86.98%) while retaining lignans in the product stream, and the regenerated DES maintained stable extraction performance, establishing the feasibility of a closed-loop solvent cycle.
5. The lignan extract exhibited strong, concentration-dependent antioxidant activity (DPPH: 89.15%, ABTS: 85.41% at 1.0 mg·mL⁻¹, respectively), demonstrating its potential as a natural antioxidant for high-value applications.

This integrated “green extraction–efficient recovery” approach provides a practical and sustainable technical model for converting underutilized agricultural by-products into high-value lignan products, contributing to both waste valorization and the advancement of green biorefinery technologies within a circular bioeconomy framework.

Declarations

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics Approval

Not applicable. This study did not involve human participants or animals.

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Author Contribution

Changhai Sun: Writing-original draft. : Yumeng Zhang Writing-original draft. : Huinan Cui Methodology. Ping Xiu: Data curation. Pingyuan Wang: Data curation. Xinran Zhang: Writing-review & editing

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Figures

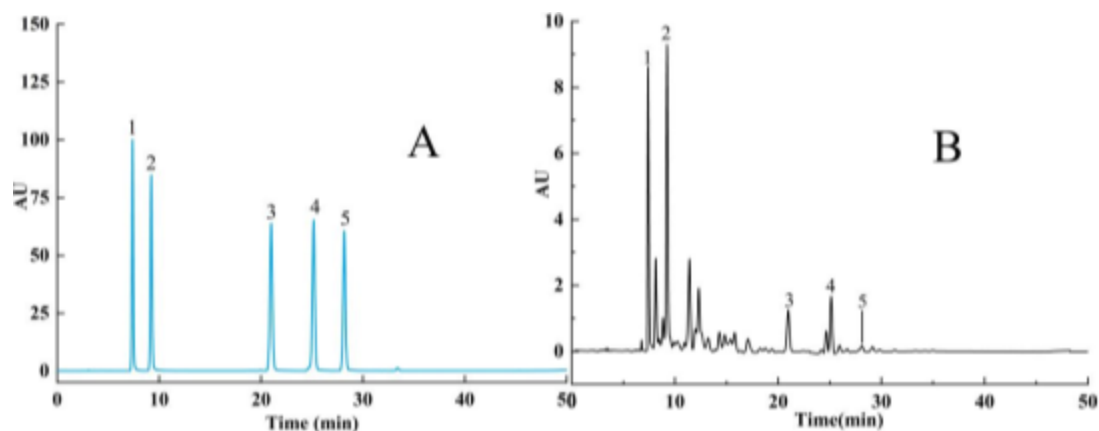


Figure 1

HPLC chromatograms at 218 nm of (A) the standard solution and (B) the extract from *Schisandra chinensis* stems. Peaks: 1=schizandrol A, 2=schizandrol B, 3=schizandrin A, 4=schizandrin B, 5=schizandrin C

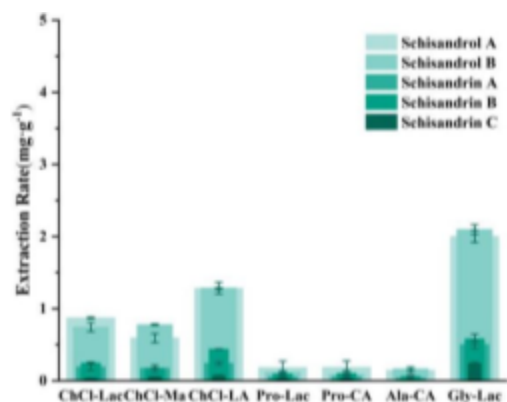


Figure 2

Lignan extraction efficiency of different DES

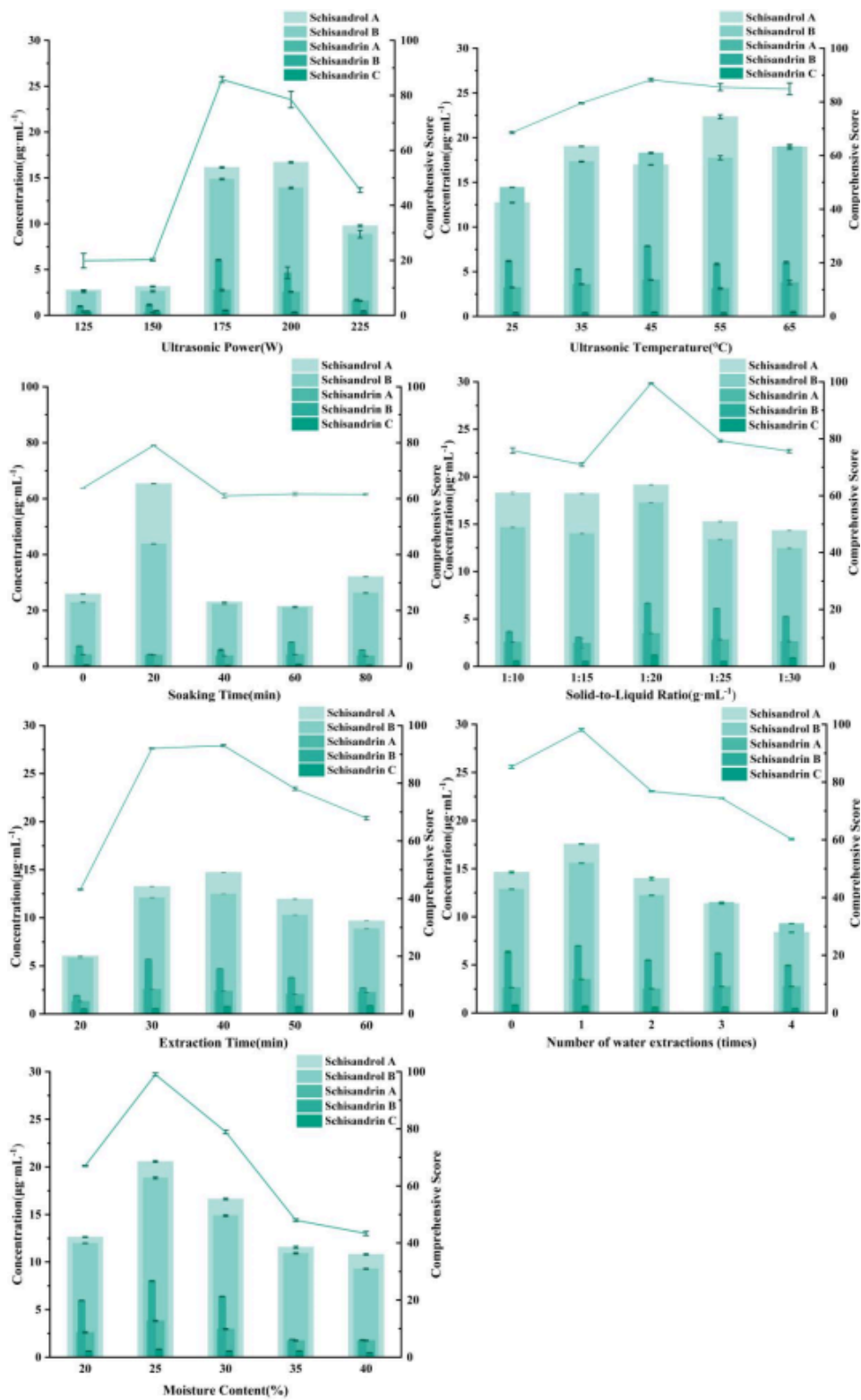
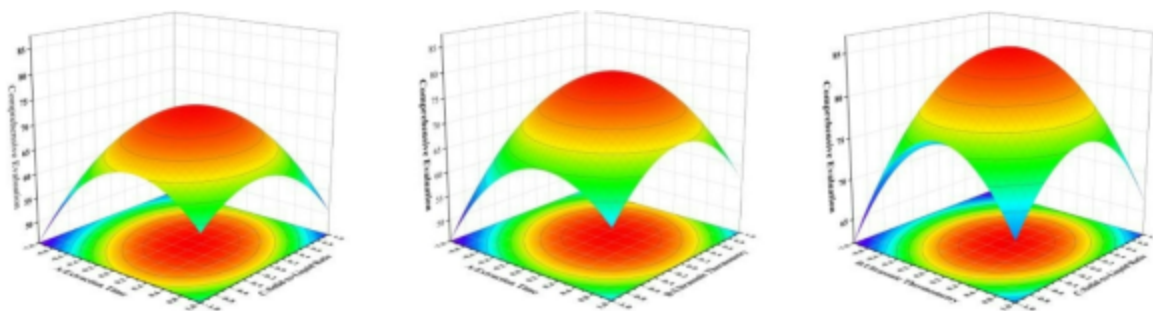


Figure 3

Results of Single-Factor Investigation



DES Recovery by Electrodialysis and Solvent Reusability

Figure 4

Response surface plots for BBD

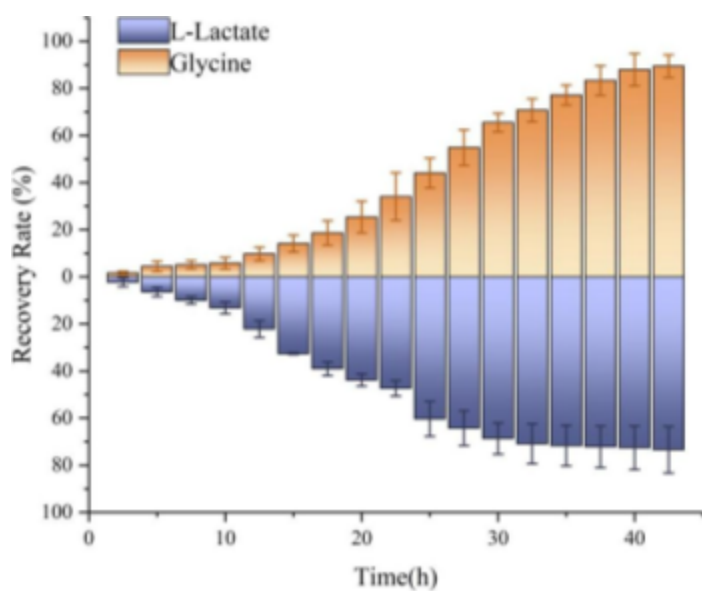


Figure 5

Recovery rate curve

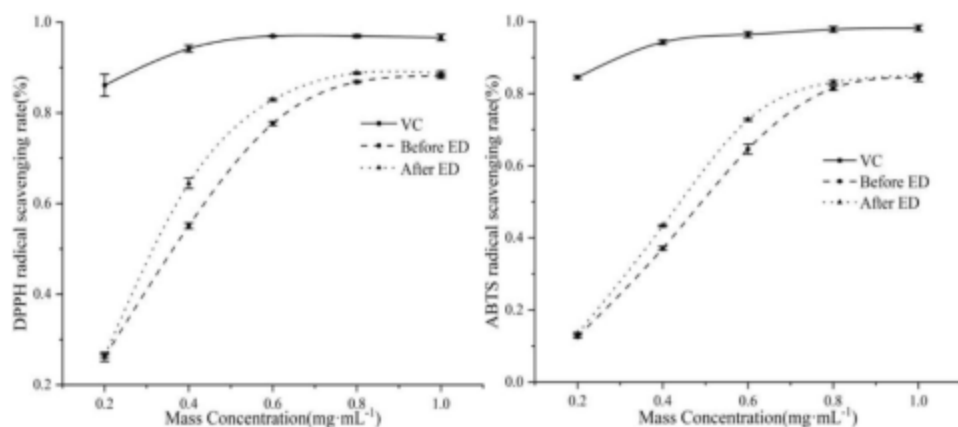


Figure 6

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