

Network and Experimental Pharmacology to Decode the Action of Wendan Decoction Against Generalized Anxiety Disorder

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Objective: The mechanism of Wendan Decoction (WDD) against Generalized Anxiety Disorder (GAD) was predicted by network pharmacology and validated by in vivo and in vitro experiments.

Methods: The targets of WDD for the treatment of GAD were obtained by a search of online databases. Further, PPI network and KEGG enrichment were used to identify the key targets and pathways. Ultimately, these key targets and pathways were validated by in vivo experiments on GAD mice modeled by repeated restraint stress (RRS) and in vitro experiments on inflammatory factor stimulated BV-2 cells.

Results: Through searching the databases, the 137 ingredients of WDD that correspond to 938 targets and 4794 targets related to GAD were identified. Among them, 569 overlapping targets were considered as the therapeutic targets of WDD for GAD. PPI analysis showed that the inflammation-related proteins IL-6, TNF, SRC and AKT1 were the key targets, and KEGG enrichment suggested that PI3K/AKT and MAPK signaling pathways were key pathways of WDD in the treatment of GAD. In vivo experiments, RRS mice exhibited abnormality in behavioristics in open field test (OFT) and elevated plus maze (EPM) and increases in serum corticosterone and the percentage of lymphocytes positive for IL-6 in peripheral blood. These abnormal changes can be reversed by WDD and the positive control drug paroxetine. In vitro experiments, WDD can inhibit IL-6 induced activation of PI3K/AKT and MAPK signaling pathways in BV2 cells, and suppress the ensuing release of inflammatory factors TNF- α , IL-1 β and PGE₂, and showed a dose-dependent effect.

Conclusion: WDD is able to resist GAD by relieving inflammatory response in peripheral and central system.

Keywords: Wendan Decoction, Generalized Anxiety Disorder, network pharmacology, Interleukin-6, PI3K/AKT signaling pathway, MAPK signaling pathway

Introduction

Generalized Anxiety Disorder (GAD) is one of the most common anxiety disorders characterized by continuously significant nervousness, autonomic hyperfunction and neuromuscular motor disturbance.¹ According to a globally joint cross-sectional epidemiological survey, 3.7% of people have suffered from GAD during their lives, and most of GAD patients had concurrent mood disorders such as major depression.^{2,3} According to epidemiology and health economics research, GAD has become a major socio-economic burden for health-care systems during the past 30 years.⁴

Selective Serotonin Reuptake Inhibitor (SSRIs) and Serotonin-norepinephrine reuptake Inhibitor (SNRIs), such as paroxetine and venlafaxine, are first-line therapeutic agents for GAD.⁵ However, most drugs have serious side effects, including nausea, constipation, insomnia and liver damage.⁶ Nowadays, the research and development of anxiolytic

medication and alternative therapy has become a hot research topic.^{7,8} Traditional Chinese medicine (TCM) has been used to treat mental and nervous system disorders for thousands of years, with the characteristics of multi-target and multi-channel due to their complex compositions. Several randomized controlled trials (RCT) have shown that TCM prescriptions such as Xiao Yao San, Renshu Powder and Qingyan Formula, have prominent therapeutic effects against GAD.^{9–11}

Wendan Decoction (WDD) is a representative formula for treating mental and neurological disorders, such as schizophrenia, insomnia and melancholia.^{12–15} It consists of Banxia (*Pinellia ternata* (Thunb.) Makino) (6 g), Zhishi (*Citrus aurantium* L.) (6g), Chenpi (*Citrus reticulata* Blanco) (9g), Zhuru (*Bambusa tuldoidea* Munro) (6g), Fuling (*Poria cocos* (Schw.) Wolf) (4.5g), Shengjiang (*Zingiber officinale* Roscoe) (6g), Dazao (*Ziziphus jujuba* Mill.) (3g) and Gancao (*Glycyrrhiza uralensis* Fisch. ex DC.) (3g), first composed by Wuze Chen, a TCM physician in 12th century. Several RCTs show that WDD can effectively improve the symptoms of anxiety patients, reduce the scores of Hamilton Anxiety Scale (HAMA) and Self-Rating Anxiety Scale (SAS), with good safety and efficacy.^{16,17} However, the holistic mechanism of WDD against GAD has not been fully revealed.

Network pharmacology, integrating systems biology and pharmacology, provides a new approach to understand the relationship between Chinese herbal prescription and disease at a systematic level.¹⁸ It is a reliable and rapid method not only contributing to exploration of active ingredients in the prescription, but also providing prediction of potential targets and pathway. In this study, network pharmacology was applied to explore the mechanisms of WDD for the treatment of GAD. In vivo and vitro experiments were used to confirm the reliability of network pharmacology.

Materials and Methods

Network Pharmacology Prediction

Collection of Active Ingredients and Targets

Ingredients of WDD and corresponding targets were extracted from Traditional Chinese Medicine Systems Pharmacology database (TCMSP, <http://tcmsp.com/tcmsp.php/>)¹⁹ and The Encyclopedia of Traditional Chinese Medicine database (ETCM, <http://www.nrc.ac.cn:9090/ETCM/>).²⁰ Pubchem database (<https://pubchem.ncbi.nlm.nih.gov/>)²¹ and SwissTargetPrediction database (<http://www.swisstargetprediction.ch/>)²² were also used for the identification of putative targets. Unified Protein Database database (UniProt, <https://www.uniprot.org/>)²³ was used for target standardization and annotation. The gene targets of disease were extracted from GeneCards database (<http://www.genecards.org/>)²⁴ and Online Mendelian Inheritance in Man database (OMIM, <https://omim.org/>)²⁵ with “Generalized Anxiety Disorder” as the keyword. We received an ethics committee waiver for using these two databases from Medical and Animal Experiment Ethics Committee of Beijing University of Chinese Medicine. A herb-target network was constructed using Cytoscape 3.7.2 software²⁶ to present the distinction of both the known targets and the putative targets.

Network Construction and Analysis of Protein-Protein Interaction (PPI)

In order to identify the key targets in WDD-GAD intersection genes, STRING database (<https://string-db.org/>)²⁷ and Cytoscape 3.7.2 software were used to construct and analyze the PPI network. In STRING database, organism was set as *Homo Sapiens*, and confidence was set as greater than 0.9, while disconnected nodes were hidden in the network. Consequently, subnetwork was constructed as their degree values became twofold the median degree of all nodes in the network.²⁸ A network topology analysis (NCA) on the related targets of WDD was carried out. Four topological features, Betweenness Centrality (BC), Closeness Centrality (CC), Degree Centrality (DC) and Eigenvector Centrality (EC) were calculated to filter out the key targets in the subnetwork by cytoNCA app.²⁹

Kyoto Encyclopedia of Genes and Genomes (KEGG) Enrichment Analysis

KEGG enrichment analysis was performed on the therapeutic targets of WDD for GAD by STRING database, which is critical to exploring pathogenesis and therapy of WDD treating GAD. In order to illustrate the complex pharmacological network of WDD more accurately, the “disease” and “metabolism” category of the KEGG terms were removed according to KEGG database (<https://www.kegg.jp/>),³⁰ and top 15 KEGG pathways of WDD are displayed in a bubble chart according to the ascending order of P value.

Experimental Verification

Reagents and Antibodies

The reagents and antibodies used in this study are as follows: RPMI 1640 medium (Gibco, USA), Fetal bovine serum (FBS, ScienCell, USA), Leukocyte activation cocktail with Golgi Plug (552843, BD, USA), 0.25% trypsin-EDTA (Gibco, USA), penicillin streptomycin (Gibco, USA), Recombinant Murine IL-6 (216-16, peprotech, USA), Dexamethasone (DEX) (sigma, USA), DMEM medium (Gibco, USA), phosphate-buffered saline (PBS, HyClone, USA), RIPA lysis buffer (Solarbio Life Sciences, China), Phenylmethane sulfonyl fluoride (PMSF) (Solarbio Life Sciences, China), Phosphatase inhibitor (Beyotime, China), CellTiter 96[®] AQueous One Solution Cell Proliferation Assay (G358A, Promga, USA), Corticosterone ELISA Kit (EIA-4164, DRG, Germany), Prostaglandin E₂ ELISA Kit (EIA-5811, DRG, Germany), TNF- α (CME0004, Beijing 4A Biotech), IL-1 β (CME0015, Beijing 4A Biotech), Formic acid (A117-50, Fisher Chemical, USA), Acetonitrile (A955-1, Fisher Chemical, USA).

PerCP/Cyanine5.5 anti-mouse CD3 Antibody (100218, BioLegend, USA), FITC anti-mouse CD4 Antibody (116004, BioLegend, USA), PE anti-mouse IL-6 Antibody (504504, BioLegend, USA), PI3K antibody (A4992, Abclonal, China), Phospho-PI3K (Y467/199) antibody (YP0224, Immunoway, USA), AKT antibody (ab8805, Abcam, UK), Phospho-AKT (S473) antibody (4060S, Cell Signaling, USA), p38 MAPK (AP0526, Abclonal, China), Phospho-p38 MAPK (A14401, Abclonal, China), β -Actin antibody (AC026, Abclonal, China), HRP conjugated goat anti-rabbit IgG (ZB-2301, Zhongshan Jingqiao Biotechnology, China).

Preparation of Drugs

WDD was purchased from China Beijing Tongrentang Co., Ltd, consisting of the following eight herbs: Banxia (Pinellia ternata (Thunb.) Makino) (6 g), Zhishi (Citrus aurantium L.) (6g), Chenpi (Citrus reticulata Blanco) (9g), Zhuru (Bambusa tuldoidea Munro) (6g), Fuling (Poria cocos (Schw.) Wolf) (4.5g), Shengjiang (Zingiber officinale Roscoe) (6g), Dazao (Ziziphus jujuba Mill.) (3g) and Gancao (Glycyrrhiza uralensis Fisch. ex DC.) (3g). The freeze-dried powder of WDD was prepared as follows: The raw herbs were soaked in nine times their weight in water for 30 min, then decocted for 1h and filtered; the process was repeated twice. The filtrates from the three procedures were mixed and concentrated to 60 mL. Anhydrous ethanol enables macromolecules such as starch to deposit via alcohol precipitation.³¹ When the concentrated solution of WDD cooled down to room temperature, an equal volume of anhydrous ethanol (60mL) was added slowly and mixed thoroughly, kept refrigerated for 12 hours at 4°C. After centrifuging, the supernatant was obtained and then heated to 60±5°C to volatilize ethyl alcohol until the mixture became a density of 1.08g·cm⁻³.³² After that, WDD was freeze-dried into powder by a lyophiliser (SCIENTZ-10N, Ningbo scientz biotechnology Co., Ltd., China) and stored in a refrigerator at -20°C. The positive control drug Paroxetine for animal experiments was purchased Zhejiang Huahai Pharmaceutical Co., Ltd.

Drug Identification and Dissolution

The freeze-dried powder of WDD was detected by liquid chromatography tandem mass spectrometry (LC-MS) to ensure that freeze-dried powder contains all key ingredients as predicted by network pharmacology. After being sterilized with 0.22 μ m micro membrane filtration, WDD extract was used for ingredient identification on Nexera High-Performance Liquid Chromatograph (Japan Shimadzu Co., Ltd) coupled to the SCIEX 5600 Triple-TOF mass spectrometer (Sciex, Toronto, Canada). The LC-MS raw data was processed in MS-DIAL 4.60 software.³³ Ingredients were identified from the perspective of sample information, peak name, retention time, mass-to-charge ratio (m/z) and peak area, by searching several mass spectral reference libraries, including MassBank (<https://massbank.eu/MassBank/>),³⁴ RIKEN MSn spectral database for phytochemicals (ReSpect, <http://spectra.psc.riken.jp/>)³⁵ and Global Natural Products Social Molecular Networking (GNPS, <https://gnps.ucsd.edu/ProteoSAFe/static/gnps-splash.jsp>).³⁶

Assuming the average human weighs 60 kg, the therapeutic dose of WDD for an adult is 0.725g/kg/d (raw herbs). According to the ratio of mice to human body surface area, mice dose is 9.1-fold higher than human therapeutic doses, thus the mice dose is 6.5975g/kg/d (raw herbs).³⁷ Correspondingly, the dose of paroxetine for a mouse is 0.0303mg/g/d. WDD and paroxetine were dissolved in distilled water and kept in 4°C until use.

Animals Feeding and Administration

A total of 40 male BALB/c mice (20±2 g) were purchased from Beijing Vital River Experimental Animal Science and Technology Co., Ltd (License No. SCXK (Jing) 2021–0006; Beijing, China). The mice were housed in a Specific Pathogen Free (SPF) facility at China-Japan Friendship Hospital, where the condition was in accordance with the National Standards for Laboratory Animals of China (GB 14925–2010). Since the animal experiment was carried out in China-Japan Friendship Hospital, the experiment was approved by the experimental animal care and welfare ethics committee of China-Japan Friendship Hospital (No.zryhyy-21-21-07-12).

After one-week adaptive feeding, 40 mice were randomly divided into blank control group, repeated restraint stress (RRS) model group, WDD group and paroxetine group. RRS was conducted by placing mice in a 50-mL conic plastic tube for 4 hours from 9:00 a.m. to 13:00 p.m. every day. Blank control group mice received no restraint stress, while mice in model group, WDD group and paroxetine group received a 14-day course of RRS.³⁸ Drug administration was conducted by gavage an hour after the end of restraint stress. beginning from 8th day to 14th day of RRS, the mice in the blank control group and RRS group received a gavage of equivalent volume distilled water every day. And the daily gavage of WDD extract or paroxetine for a mouse in the WDD or paroxetine group.

After 14-day administration, behavioral tests were carried out.³⁹ Then, the mice were anesthetized with isoflurane, and blood samples were obtained from abdominal aorta in heparin tube. Of whole blood samples, 200ul were used for flow cytometry assays. The remaining blood samples were centrifuged to isolate the plasma, which was used for detection of corticosterone concentration by Enzyme-linked immunosorbent assay (ELISA). After collection of blood samples, the mouse was sacrificed for CO₂ asphyxiation.

Cell Culture and Drugs Administration

Bv2 cells (CS0271) were purchased from *Beijing Dingguo Changsheng Biotechnology Co.Ltd.* China. After resuscitation, Bv2 cells were cultured in DMEM complete medium (containing 90% DMEM, 10% FBS, 100 U/mL penicillin and 100 µg/mL streptomycin) in a standard cell culture incubator (5% CO₂, 37°C).⁴⁰ Once monolayer cell confluence was observed, the cell passage was carried out at a ratio of 1:2–1:3 with 0.25% EDTA-trypsin digestion.

In vitro, WDD powder was dissolved in PBS to different concentrations and added to cell culture medium. In order to determine the maximum tolerated dose, the MTS assay was employed to test cell viability.⁴¹ Subsequently, 1×10⁶ cells were seeded into 6-well plates and allowed to attach overnight. After being completely adherent, the cells were then pretreated with WDD and the positive control drug DEX for 1 h. 10 ng/mL of IL-6 was then added to induce a pro-inflammatory phenotype. Following 12-hour incubation, the culture supernatant was analyzed using ELISA assay and the cells were lysed for western blot (WB) assay.

Behavioral Tests

Open field test (OFT) and elevated plus maze (EPM) were employed to examine anxiety-like behaviors of mice. All the mice were placed in the behavior laboratory for 1 hour to habituate themselves to the environment before tests.⁴²

Open-field apparatus with a camera right above consisted of a 50 cm³ cube space, whose floor was evenly divided into 25 zones (9 central zones and 16 surrounding zones).⁴³ At the beginning of the experiment, the mice were deposited in the center of the open-field apparatus with the camera turning on to record the 5-minute track of each mouse. All the videos were analyzed using a professional software system (Ethovision XT 15, Noldus).

EPM apparatus consisted of two oppositely positioned open arms (66cm×5cm), two oppositely positioned enclosed arms (66cm×5cm) and a central square platform (5cm×5cm) from which four black arms radiated.⁴⁴ The maze was elevated to a height of 50 cm from the floor. Mice were placed individually into the central platform facing toward an open arm and allowed free exploration of the apparatus. An arm entry was defined as the entry of two fore limbs into one arm.

ELISA

The plasma corticosterone and cell supernatant were analyzed for TNF-α, IL-1β and PGE₂ by commercialized ELISA kit according to the instruction.^{45,46} The optical density (OD) value of each sample was read at 450 nanometers by a microplate reader. A standard curve was plotted according to OD of the concentration of standards by CurveExpert 1.4. The concentration of each sample were calculated with reference to a standard curve.

Flow Cytometry

Percentage of IL-6⁺CD3⁺CD4⁺ lymphocytes cells was examined by flow cytometry. 200µL blood sample was mixed with 200µL RPMI-1640 complete medium. Lymphocytes were stimulated by leukocyte activation cocktail and Golgi plug and incubated for 6 hours.⁴⁷ Subsequently, CD3 and CD4 antibodies were added into the sample for 15-minutes incubation. After lysing erythrocytes and fixing monocytes, the sample was added IL-6 antibody and incubated again in the dark at 4°C for 30 minutes. Finally, the samples were analyzed using the LSRFortessa flow cytometer (BD LSRFortessa, Becton, Dickinson and Company, USA).

Cell Viability Assay

Cell viability was measured by MTS assay. Bv2 cells were diluted to a concentration of 5×10^4 cells/mL. The cell suspensions were seeded in a 96-well plate, with 100 µL in each well at an average density of 5×10^3 cells per well. After the cells adhered to the wall, WDD was added to each well to final concentrations of 100, 200, 300, 400, 500, 600, 700, 800, 900 and 1000 µg/mL. After incubation 12 hours, the medium was replaced by fresh complete DMEM complete medium 100 µL per well. Another 2-hours incubation later, each well was added 20 µL MTS. Incubation was continued for an additional 2 hour, and the optical density (OD) value was measured with a microplate reader at 490 nm wavelength. Cell viability was calculated according to the equation following: viability (%) = $100 \times (\text{OD of treated sample} - \text{OD of medium}) / (\text{OD of control sample} - \text{OD of medium})$. The high dose was defined as the maximum concentration of WDD extract that had no effect on cell proliferation compared with blank group. Half maximal concentration was defined as a medium dose, and one quarter of maximal concentration was defined as a low dose.⁴¹

Western Blot

After the intervention, cells were washed with PBS and lysed with RIPA lysis buffer (containing 1%PMSF and 1% phosphatase inhibitor) on ice for 30 minutes. The supernatant was collected after centrifugation. Protein concentration was performed via the bicinchoninic acid (BCA) method.⁴⁸ The concentration of each extracted sample was corrected. Quantified proteins were mixed with 5×loading buffer and boiled at 100°C for 10 minutes. The samples were sub-packed and stored at -80°C until use.

Proteins were separated by SDS-PAGE gel electrophoresis under 120V and transferred to PVDF membranes on ice-bath under 80V, 50min. Afterwards, PVDF membranes were blocked with 5% skimmed milk powder in TBST at room temperature for 1 h. The membranes were incubated with primary antibody at 4°C overnight and secondary antibody for 1 hour at room temperature. Finally, blot visualization was carried out by chemiluminescence imaging system (ChemiScope 6100, Shanghai Qinxiang Scientific Instrument Co., Ltd). The grey value was measured by Image J software.⁴⁹

Statistical Analysis

Experimental data were analyzed by unpaired two-tailed Student's t-tests of the means between two groups. GraphPad Prism software version 5.01 (GraphPad Software Inc., CA, United States) was utilized to determine the statistical significance in comparisons. A P value of <0.05 was set for statistical significance. All the error bars shown in figures represent standard error of the mean (SEM).

Results

Ingredients and Targets of WDD

A total of 137 ingredients were screened out from TCMSP and ETCM, and detailed chemical parameters of all ingredients in each herb are listed in [Supplementary Table 1](#). The 137 ingredients of 8 herbs corresponding to 938 targets ([Supplementary Table 2](#)), 4794 targets related to GAD were identified ([Supplementary Table 3](#)). Among them, 569 targets overlap ([Supplementary Table 4](#)), which were considered the therapeutic targets of WDD against GAD. Medicine composition of WDD, the therapeutic targets of WDD against GAD and their relationship are presented in [Figure 1](#).

Construction and Analysis of Protein-Protein Interaction (PPI)

The therapeutic targets of WDD against GAD were input into STRING database and subjected to PPI analysis. PPI network was constructed based on confidence >0.9 and Degree Centrality topology analysis was performed on the

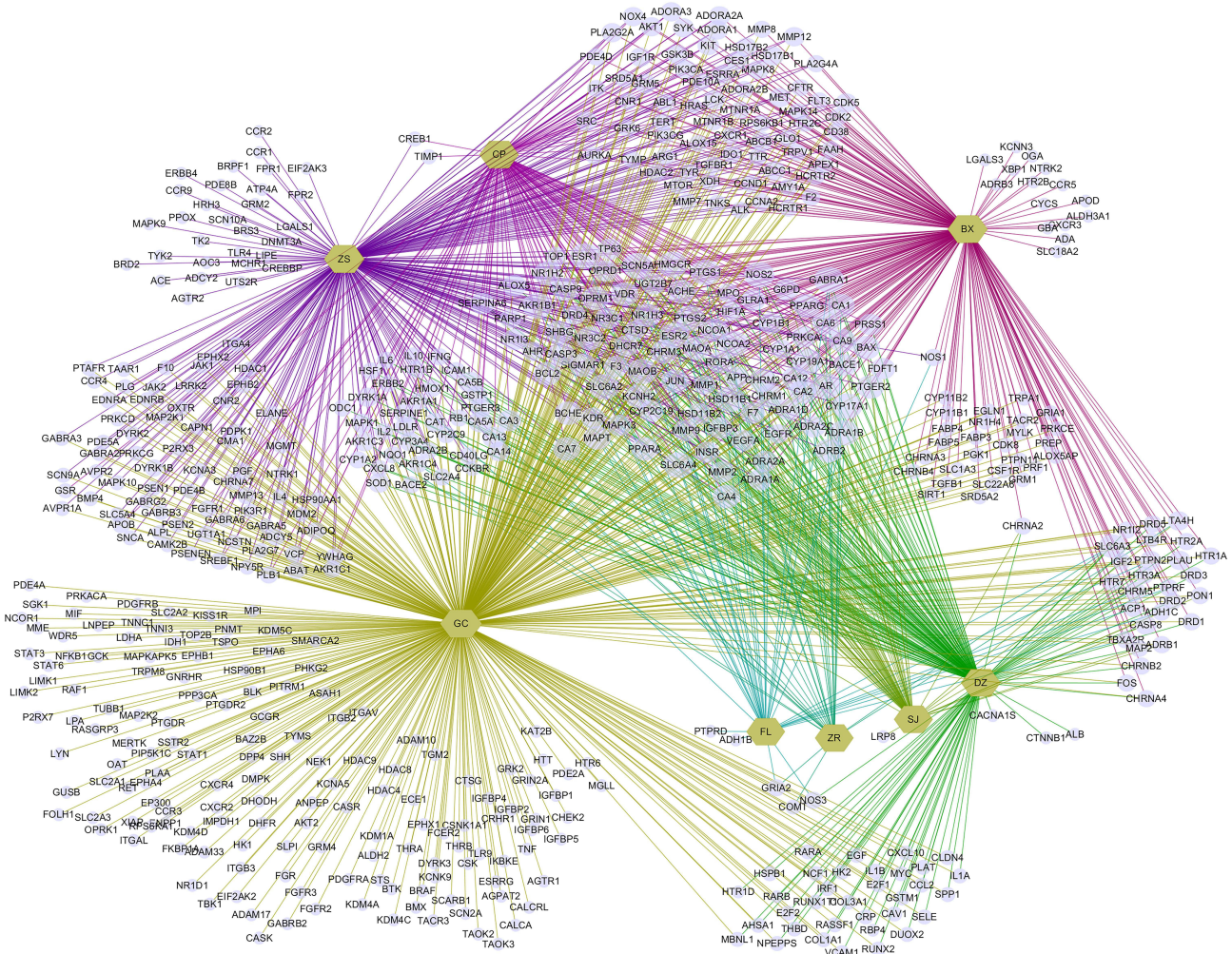


Figure 1 The herb-target network of Wendan Decoction (WDD) treating Generalized Anxiety Disorder (GAD). Yellow nodes represent all herbs of WDD. Blue nodes represent the intersection targets of WDD and GAD. Common targets of multiple herbs are located in the center of the network. **Abbreviations:** BX, *Pinellia ternata* (Thunb.) Makino; ZS, *Citrus aurantium* L; CP, *Citrus reticulata* Blanco; ZR, *Bambusa tuldoidea* Munro; FL, *Poria cocos* (Schw) Wolf; SJ, *Zingiber officinale* Roscoe; LZ, *Ziziphus jujuba* Mill; GC, *Glycyrrhiza uralensis* Fisch. ex DC.

selected targets. A total of 142 genes that were twice greater than the median were filtered out and imported into PPI topological analysis. The central targets of PPI network were IL6 and TNF (inflammatory cytokines), SRC (protein tyrosine kinases), and AKT1 (the core of PI3K/AKT signaling pathway) (Figure 2).

KEGG Enrichment Analysis

The therapeutic targets of WDD for GAD treatment were introduced into KEGG enrichment analysis. A total of 226 KEGG terms whose P value <0.05 were obtained from STRING database (Supplementary Table 5). In order to illustrate the complex pharmacological network of WDD more accurately, the “disease” and “metabolism” category of the KEGG terms were removed, and top 15 KEGG pathways of WDD are displayed in a bubble chart according to the ascending order of P value. The interaction of targets and pathways of WDD for GAD treatment is presented in Figure 3.

LC-MS

The ingredients of each herb that correspond to most targets in network pharmacology were defined as the representative one. Beta-sitosterol and baicalein are the representative ingredients of *Pinellia ternata* (Thunb.) Makino; luteolin and naringenin of *Citrus aurantium* L.; naringenin of *Citrus reticulata* Blanco; coniferyl aldehyde and syringaldehyde of

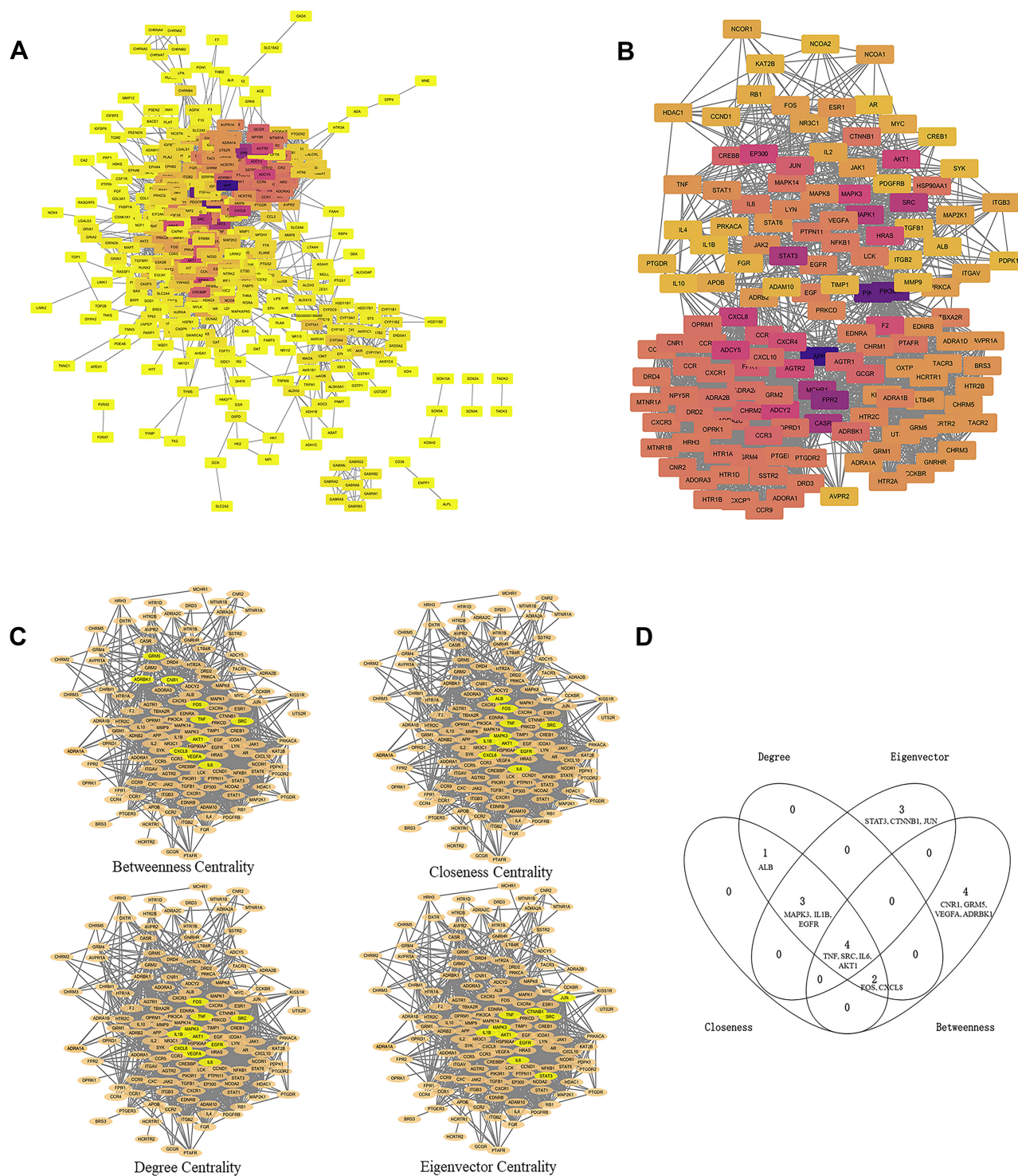


Figure 2 PPI topological analysis of Wendan Decoction treating Generalized Anxiety Disorder. **(A)** PPI network of 569 targets. **(B)** The subnet of PPI with 142 hub targets screened based on twice medium degree. **(C)** According to the Betweenness Centrality, Closeness Centrality, Degree Centrality and Eigenvector Centrality separately, TOP 10 targets in subnet from each criterion were labeled yellow. **(D)** Venn diagram of 4 topological analysis data. TNF, SRC, IL-6 and AKT1 were common targets.

Bambusa tuldoides Munro; hederagenin of *Poria cocos* (Schw.) Wolf; beta-sitosterol of *Zingiber officinale* Roscoe; quercetin and beta-sitosterol of *Ziziphus jujuba* Mill.; glabridin, quercetin and naringenin of *Glycyrrhiza uralensis* Fisch. ex DC. LC-MS detection suggested that they were all available in the samples of WDD we prepared (Figure 4), with specific information for each ingredient shown in Table 1.

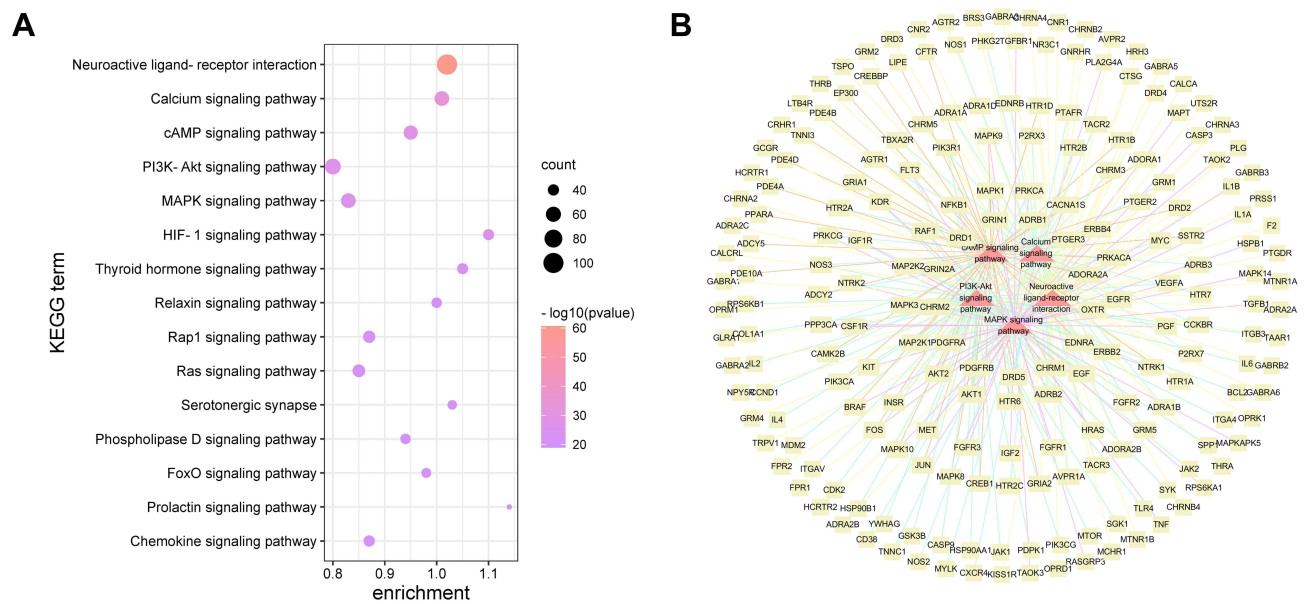


Figure 3 (A) KEGG enrichment analysis of 569 intersection targets of Wendan Decoction and Generalized Anxiety Disorder. The redder bubble is, the less P value is. (B) Network of top 5 KEGG pathways and their corresponding targets. Red nodes represent pathways. Yellow nodes represent related targets.

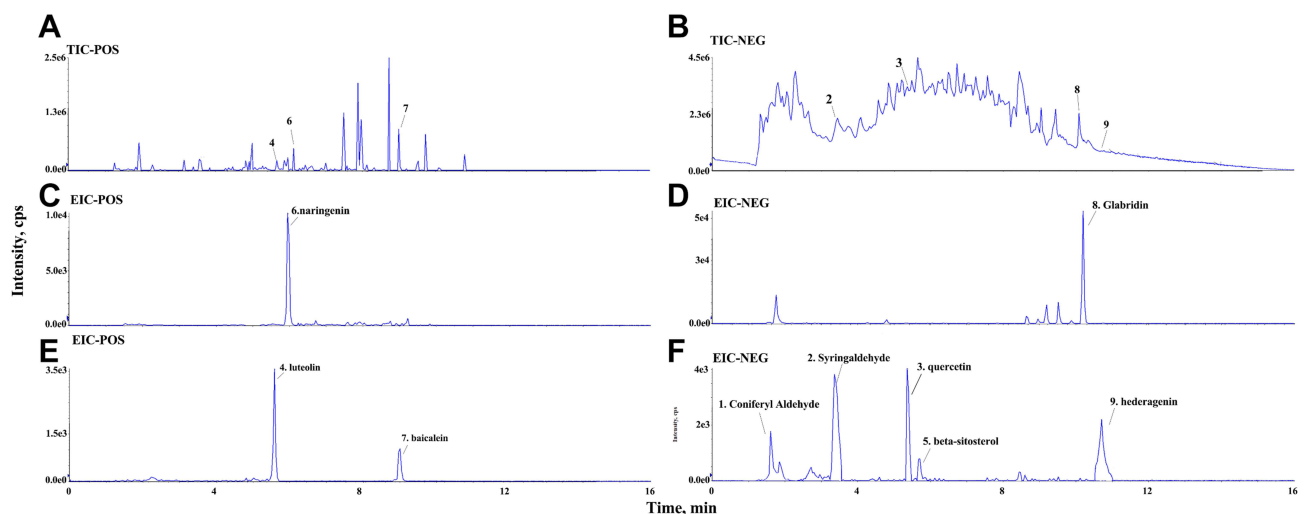


Figure 4 Identification of active ingredients of Wendan Decoction. (A) Total ion chromatography (TIC) on positive of Wendan Decoction. (B) TIC on negative of Wendan Decoction. (C-F) Extraction ion chromatography of Wendan Decoction. (C) Identification of naringenin. (D) Identification of glabridin. (E) Identification of luteolin and baicalein. (F) Identification of coniferyl aldehyde, syringaldehyde, quercetin, beta-sitosterol and hederagenin.

Effect of WDD on Mice Representations of Behavior Tests

Both open field test and elevated plus maze test were used to evaluate to what extent anxiety-like behaviors of mice were. The results indicated that model mice showed fewer time in the central zone compared with normal mice in the open field test and exhibited the stronger preference for closed arms than open arms in the elevated plus maze test. The above identified mice had developed successful anxiety-models. WDD and the positive control drug paroxetine can significantly reverse anxiety-like behaviors of mice (Figure 5).

Effect of WDD on Serum CORT

The levels of CORT in the serum of mice were measured by ELISA, which suggested that CORT in the serum of RRS model mice markedly increased. WDD and the positive control drug paroxetine can successfully decrease CORT in the serum (Figure 6).

Table I Chemical Identification of Wendan Decoction

No	RT/ (min)	Name	Formula	Ion	Cal./ (m/z)	Mea./ (m/z)	Error/ (ppm)	MS/MS	Herb
1	1.56	Coniferyl Aldehyde	C ₁₀ H ₁₀ O ₃	M-H	177.0557	177.0563	9.485	177.0563	Bambusa tuldoides Munro
2	3.39	Syringaldehyde	C ₉ H ₁₀ O ₄	M-H	181.0506	181.051	8.09	181.051, 121.0471	Bambusa tuldoides Munro
3	5.37	Quercetin	C ₁₅ H ₁₀ O ₇	M-H	301.0353	301.0351	2.727	301.0351, 151.0012, 107.0213	Ziziphus jujuba Mill., Glycyrrhiza uralensis Fisch. ex DC.
4	5.58	Luteolin	C ₁₅ H ₁₀ O ₆	M +H	287.055	287.0553	0.994	287.0553, 153.0176	Citrus aurantium L.
5	5.68	Beta-sitosterol	C ₂₉ H ₅₀ O	M-H	413.3788	413.3779	0.26	413.3779	Pinellia ternata (Thunb.) Makino, Zingiber officinale Roscoe, Ziziphus jujuba Mill.
6	5.96	Naringenin	C ₁₅ H ₁₂ O ₅	M +H	273.0757	273.0761	1.282	273.0761, 153.0188, 119.0496	Citrus reticulata Blanco, Citrus aurantium L., Glycyrrhiza uralensis Fisch. ex DC.
7	9.06	Baicalein	C ₂₁ H ₁₈ O ₁₁	M +H	447.0921	447.0928	1.369	447.0928, 271.0601	Pinellia ternata (Thunb.) Makino
8	10.20	Glabridin	C ₂₀ H ₂₀ O ₄	M-H	323.1288	323.1293	4.687	323.1293, 147.1480	Glycyrrhiza uralensis Fisch. ex DC.
9	10.70	Hederagenin	C ₃₀ H ₄₈ O ₄	M-H	471.3479	471.3484	3.211	471.3484, 407.3361	Poria cocos (Schw.) Wolf

Effect of WDD on Lymphocyte Subpopulations Positive for IL-6 in the Peripheral Blood

The cell markers CD3, CD4 and IL-6 were assayed using flow cytometry to differentiate between CD3⁺T lymphocyte subpopulations, CD3⁺ CD4⁺T lymphocyte subpopulations and CD4⁺ IL-6⁺T lymphocyte subpopulations in peripheral blood. After mice underwent RRS, their peripheral blood showed no significant changes in CD3⁺T lymphocyte subpopulations, CD3⁺ CD4⁺T lymphocyte subpopulations, but the proportion of CD4⁺ IL-6⁺ lymphocytes was remarkably increased. After the intervention of WDD and paroxetine, the proportion of CD4⁺ IL-6⁺ lymphocytes decreased (Figure 7). The above proved that inflammatory response was activated after RRS but partly inactivated by WDD and paroxetine.

Effect of WDD on the Vitality of BV2 Cells

Different concentrations of WDD were used to intervene in BV2 cells. It was found that the proliferation of BV2 cells was inhibited significantly when the concentration was higher than 700 µg/mL (Figure 8). Thus, 700 µg/mL was selected as the maximum concentration of WDD against BV2 cells, with 350 µg/mL to be the medium concentration and 175 µg/mL to be the low concentration, for subsequent experiments.

Effect of WDD on the Secretion of Inflammatory Factors in IL-6 Stimulated BV2 Cells

After BV2 cells were stimulated with 10 ng/mL of IL-6, the inflammatory factors TNF-α, IL-1β and PGE₂ were significantly increased in the cell supernatant, and the change was reversed by WDD with a dose-dependent effect. The positive control drug DEX at the concentration of 100 µmol/L was also able to inhibit the secretion of these inflammatory factors (Figure 9).

Effect of WDD on PI3K/AKT and MAPK Pathways in IL-6 Stimulated BV2 Cells

After the stimulation of BV2 cells with 10 ng/mL IL-6, the phosphorylation levels of PI3K, AKT and MAPK p38 were significantly increased, suggesting that the PI3K/AKT and MAPK signaling pathways were abnormally

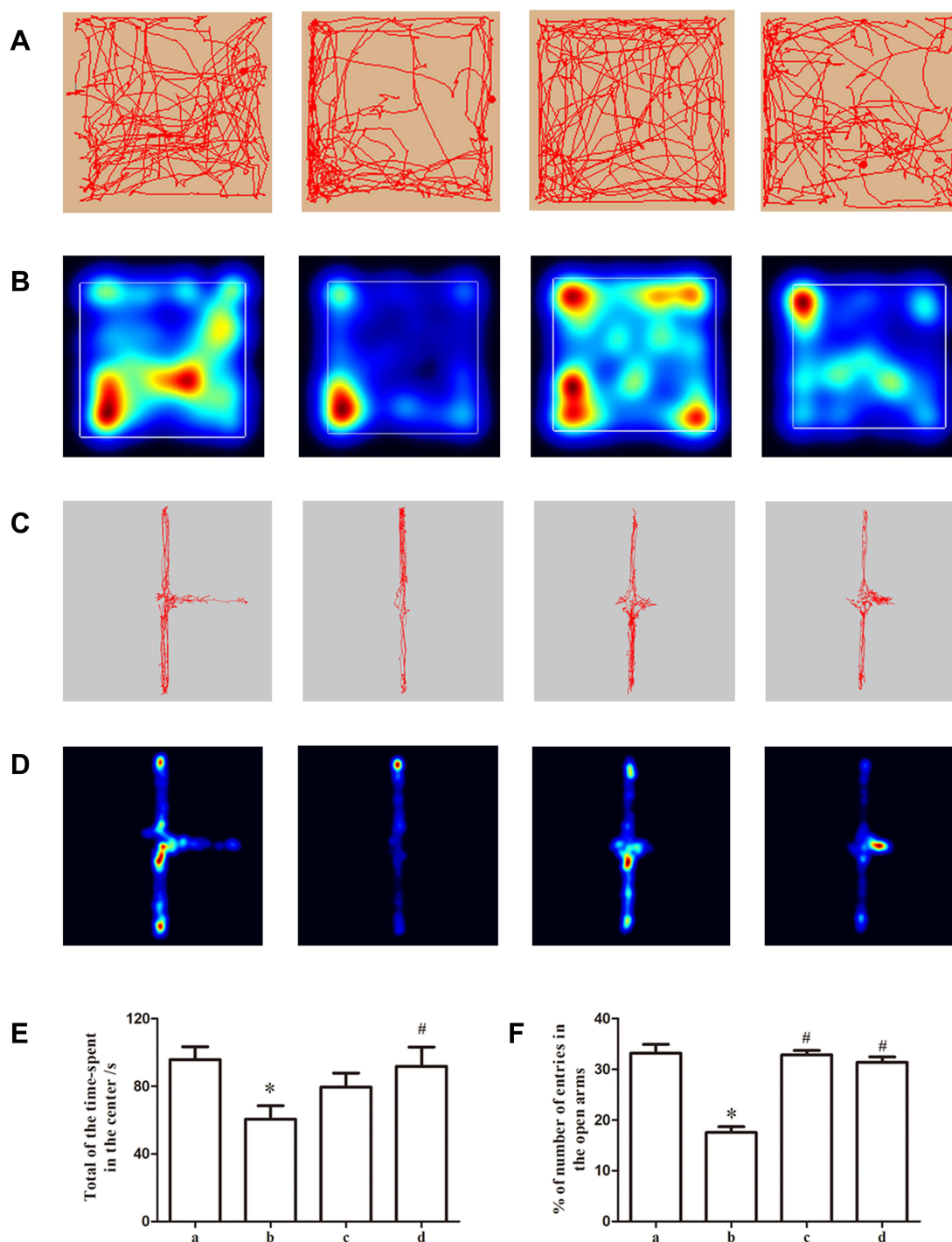


Figure 5 Behavioristic changes of mice in each group. **(A)** Representative trajectory diagram of each group in open field test. **(B)** Representative heat maps of the movement of each group in open field test. **(C)** Representative trajectory diagram of each group in elevated plus maze. **(D)** Representative heat maps of the movement of each group in elevated plus maze. **(E)** Total time spent in the central zone of open field. **(F)** Percentage of number of entries in the open arms. (a) blank control group; (b) repeated restraint stress (RRS) model group; (c) Wendan Decoction group; (d) paroxetine group. * $P < 0.05$, compared with blank control group; # $P < 0.05$, compared with RRS model group.

activated. WDD was able to reverse the phosphorylation levels of these key proteins with a dose-dependent effect. As a positive control drug, DEX at 100 $\mu\text{mol/L}$ also exerted the inhibitory effect that was superior to the high dose of WDD (Figure 10).

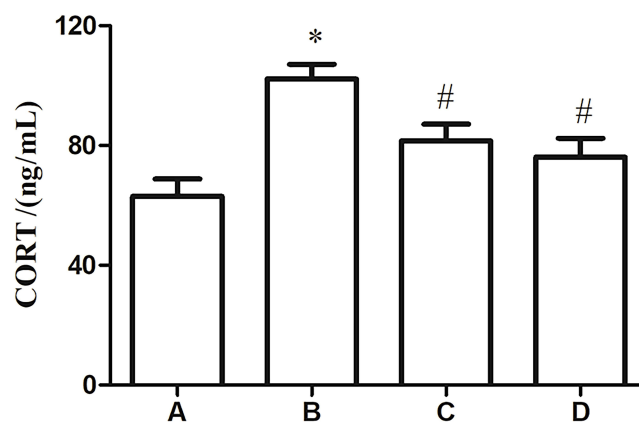


Figure 6 Plasma corticosterone concentration of mice in each group. (A) blank control group; (B) repeated restraint stress (RRS) model group; (C) Wendan Decoction group; (D) paroxetine group. *P < 0.05, compared with blank control group; #P < 0.05, compared with RRS model group.

Discussion

Persistent chronic stress abnormally activates the HPA axis, which is an important factor in the development of chronic inflammatory responses and anxiety.^{50–53} Repeated restraint stress (RRS) model is established by imposing sustained stress response on animals through long-term restraint typically used to stimulate GAD that is accompanied by hypercortisolism and anxiety-like behaviors.⁵⁴ In the present study, we established a mouse model of RRS based on previous literature and found that RRS models spent shorter dwell times in the central zones (open field test) and in the open arms (EPM test) than normal mice, as well as exhibited a significant increase in serum corticosterone. The above reflected that the model was successfully replicated and was adequate for subsequent experiments.⁵⁵ The abnormalities in ethology and corticosteroids of RRS mice were effectively reversed by WDD and the positive control drug paroxetine, suggesting that WDD is used as an antidepressant.

To further investigate therapeutic mechanism of WDD against GAD, network pharmacology was employed to predict the molecules, targets and signaling pathways that play a key role in the course of treatment. By means of network pharmacology, we determined the core ingredients with the most targets of each herb, including beta-sitosterol, baicalein, luteolin, naringenin, coniferyl aldehyde, syringaldehyde, hederagenin, quercetin, glabridin. LC-MS found that all these molecules were present in the aqueous extract of WDD we prepared. After a systematic literature search, naringenin,⁵⁶ quercetin,^{57,58} glabridin,⁵⁹ beta-sitosterol,⁶⁰ luteolin^{61,62} of them was the candidate molecule for anxiety. Among them, the anxiolytic effects of quercetin, luteolin and narigenin are closely related to the inhibition of inflammatory response, suggesting that inhibition of inflammatory response may be the potential mechanism of Wendan Decoction in treating GAD.^{57,61}

The PPI results reveal that IL-6, TNF, SRC and AKT1 are the key targets of WDD in the treatment of GAD. KEGG enrichment analysis suggests that mechanism of WDD for GAD treatment is closely correlated with neuroactive ligand receptor interaction, calcium signaling pathway, cAMP signaling pathway, PI3K/AKT signaling pathway and MAPK signaling pathway. In lymphocytes, SRC kinase regulates the transcription and synthesis of IL-6 and TNF- α by regulating downstream AKT phosphorylation and by activating the NF- κ B signaling pathway. In the central nervous system, inflammatory factors activate the PI3K/AKT and MAPK signaling pathways in microglia via the calcium and cAMP signaling pathways, and further exacerbate the inflammatory response in the central nervous system by promoting the synthesis of new inflammatory factors.^{63,64} Previous studies have shown that IL-6 is closely related to anxiety, and its activation of inflammatory responses in the central system may be a key mechanism for the occurrence and development of anxiety.^{65,66} In summary, stress contributes to inflammation of the peripheral and central nervous system mediated by IL-6, resulting in anxiety disorder. WDD might exert an anti-anxiety effect through anti-inflammation pharmacological effects (Figure 11).

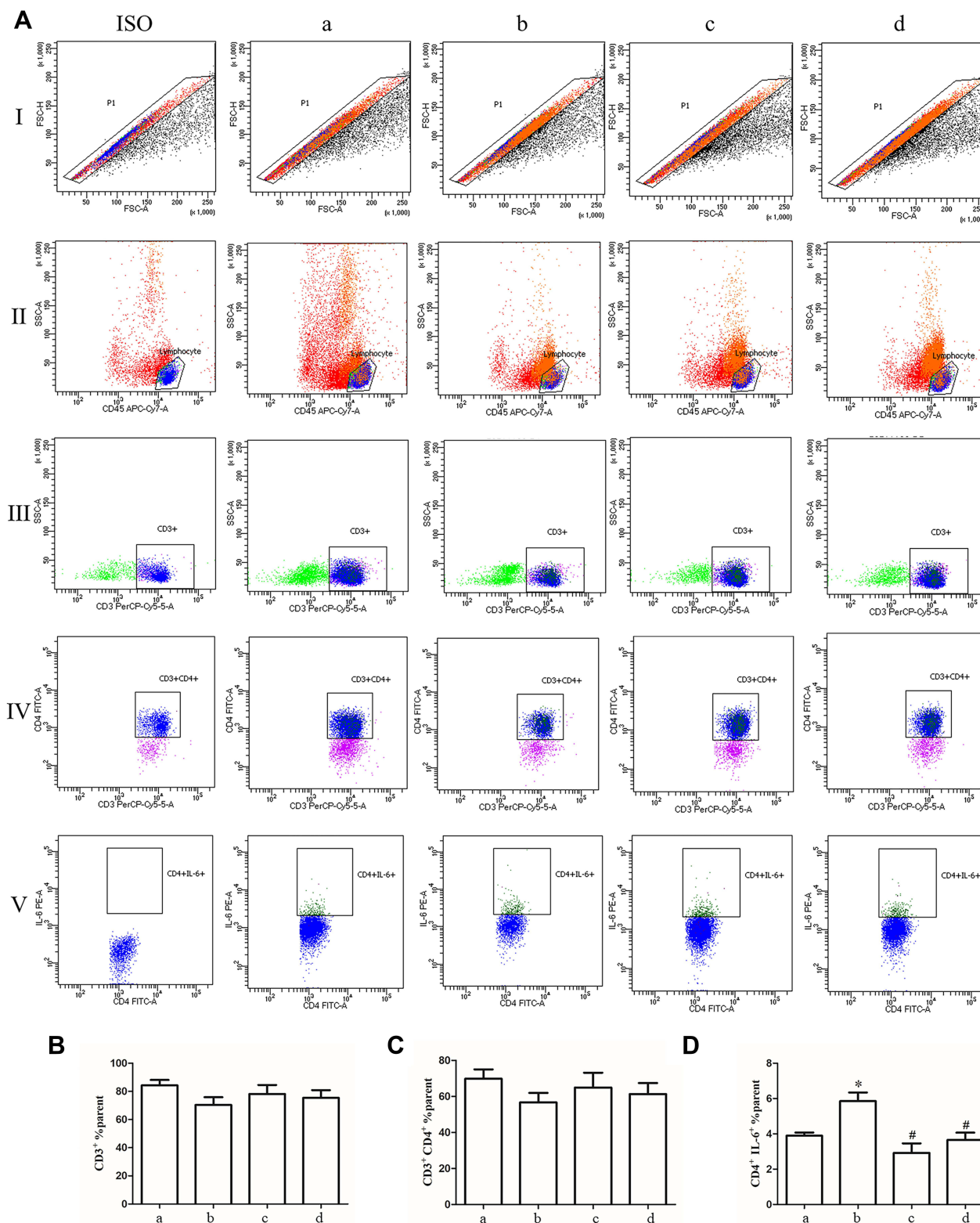


Figure 7 Percent of IL-6⁺ T lymphocytes in blood of mice in each group. **(A)** Representative flow cytometric analysis. (I) Sorting cell fragments and cells; (II) Sorting cells and T lymphocytes; (III) sorting T lymphocytes and CD3⁺ T lymphocytes; (IV) Sorting CD3⁺ T lymphocytes and CD3⁺ CD4⁺ T lymphocytes; (V) Sorting CD3⁺ CD4⁺ T lymphocytes and IL-6⁺ CD4⁺ T lymphocytes. **(B)** The proportion of CD3⁺ lymphocytes. **(C)** The proportion of CD4⁺ lymphocytes. **(D)** The proportion of IL-6⁺ CD4⁺ T lymphocytes. (a) blank control group; (b) repeated restraint stress (RRS) model group; (c) Wendan Decoction group; (d) paroxetine group. *P < 0.05, compared with blank control group; #P < 0.05, compared with RRS model group.

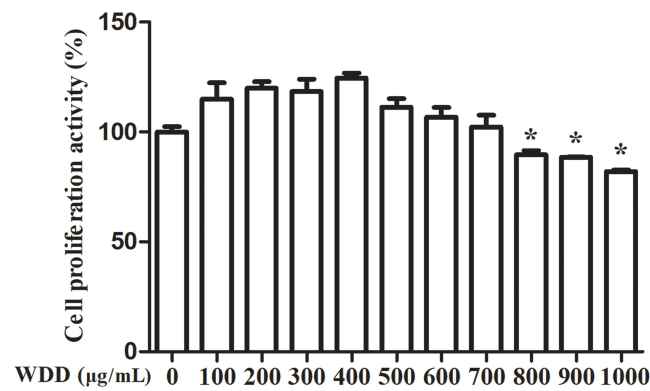


Figure 8 Effects of different concentrations of Wendan Decoction (WDD) on BV2 microglial cell proliferation. *P < 0.05, the proliferation of BV2 cells was inhibited, compared with blank control group.

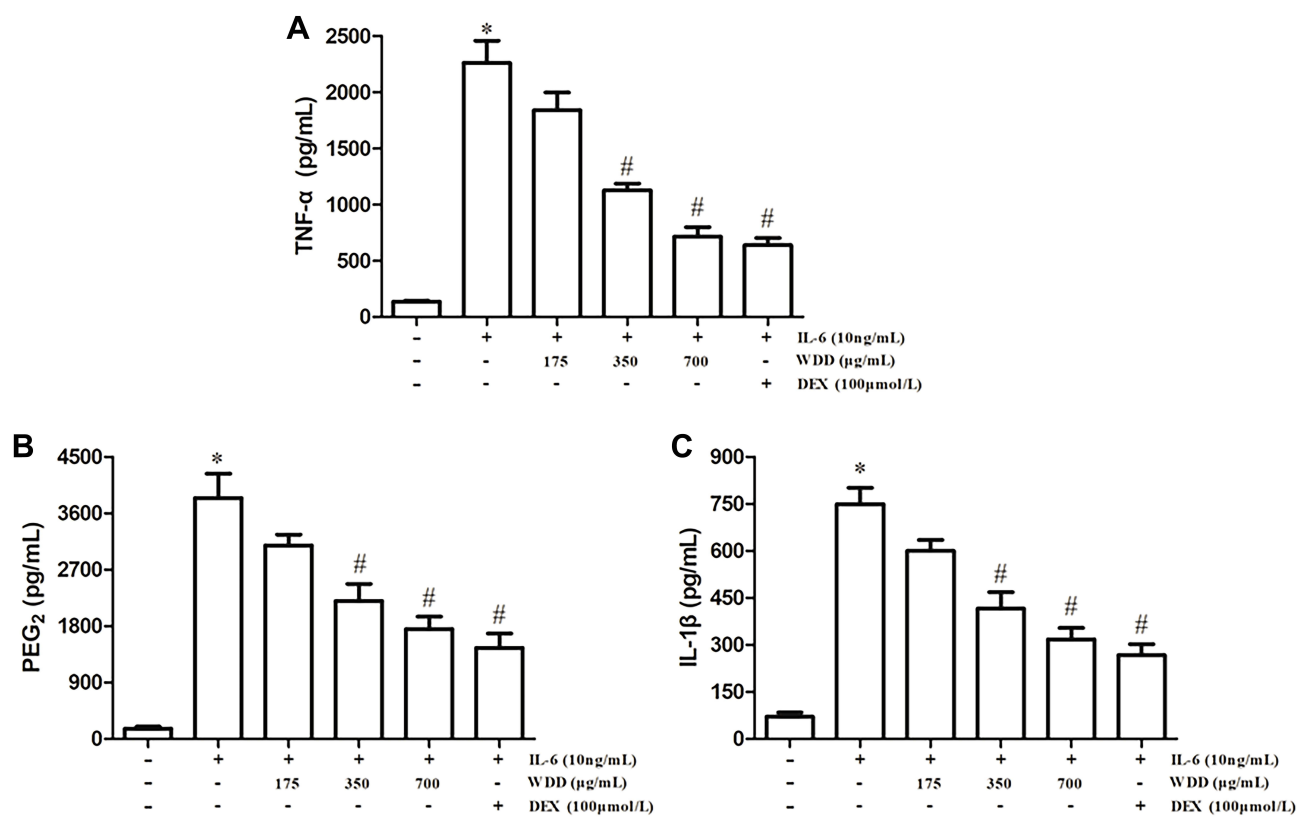


Figure 9 Effect of different concentrations of Wendan Decoction (WDD) and 100μmol/L Dexamethasone (DEX) on pro-inflammatory factors of IL-6 induced BV-2 microglia cells, respectively. (A) Concentrations of TNF-α in the cell supernatants. (B) Concentrations of PEG₂ in the cell supernatants. (C) Concentrations of IL-1β in the cell supernatants. *P < 0.05, compared with blank control group; #P < 0.05, compared with IL-6-induced group.

In the *in vivo* experiments, we measured the proportion of lymphocytes positive for IL-6 in the peripheral blood of mice by flow cytometry. The results showed that the proportion of lymphocytes positive for IL-6 was elevated in RRS mice, suggesting an activated peripheral inflammatory response in this model. WDD and Paroxetine can inhibit the above change. In the *in vitro* experiments, we stimulated BV2 cells (an immortalized mouse glial cell) by IL-6, whose results showed that IL-6 could significantly increase the ratio of p-PI3K/PI3K, p-AKT/AKT and p-p38/p38,

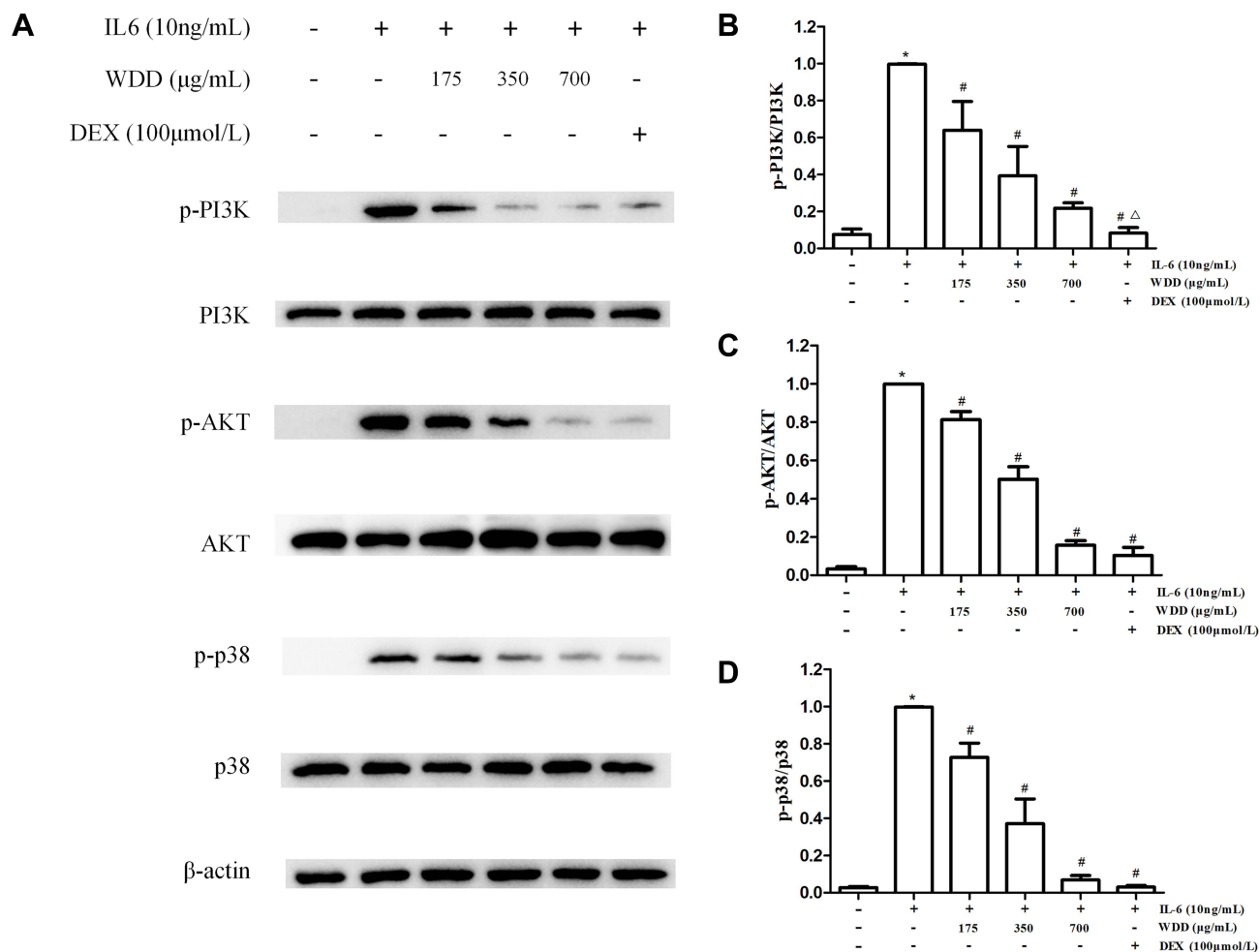


Figure 10 Effect of different concentrations of Wendan Decoction (WDD) and 100 $\mu\text{mol/L}$ Dexamethasone (DEX) on PI3K/AKT and MAPK signaling pathways of IL-6 induced BV-2 microglia cells. (A) Western blots of PI3K, p-PI3K, AKT, p-AKT, MAPK p38 and p-MAPK p38. (B) Quantification analysis of p-PI3K/PI3K. (C) Quantification analysis of p-AKT/AKT. (D) Quantification analysis of p-p38/p38. * $P < 0.05$, compared with blank control group; # $P < 0.05$, compared with IL-6-induced group; $\Delta P < 0.05$, compared with 700 $\mu\text{g/mL}$ WDD intervention group.

indicating that PI3K/AKT signaling pathway and MAPK signaling pathway were activated. Simultaneously, the inflammatory factors IL-1 β , TNF- α and PGE₂ markedly enhanced. The activation of these inflammatory pathways and the release of inflammatory factors could be reversed by WDD and positive control drugs. It is suggested that WDD may inhibit the process of aseptic inflammatory response caused by anxiety to some extent.

Limitations

However, there are limitations in our study. We only verified that WDD could inhibit the inflammation in the peripheral and central nervous system. KEGG analysis reported that neuroactive ligand-receptor interaction pathway plays an important role in the treatment of WDD against GAD. Activated microglia may overproduce the inflammatory cytokines, leading to neuronal apoptosis, neurotransmitter dysfunction and intensifying anxiety.^{67,68} In the future, we would explore the potential pharmacological mechanism of WDD against GAD through neuroactive ligand-receptor interaction.

Conclusion

In summary, animal experiments confirmed that WDD is a potent prescription to improve anxiety-like behavior and plasma corticosterone level. Subsequent network pharmacology predicts that anti-inflammation might be the mechanism of WDD for GAD treatment. In vivo, we revealed that WDD can decrease the ratio of CD4⁺IL-6⁺ T cells triggered by

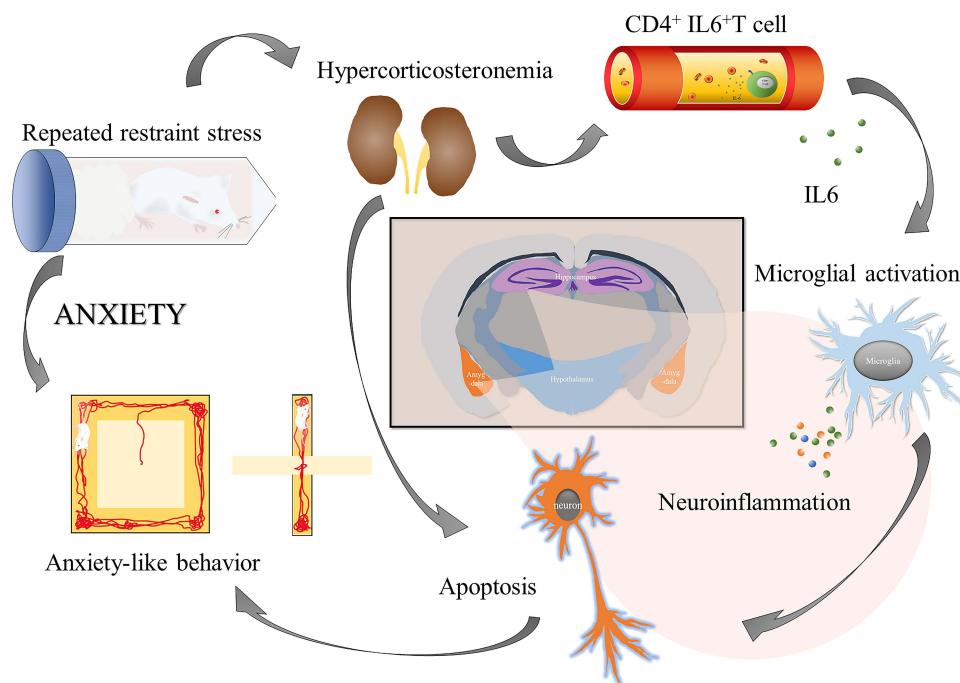


Figure 11 The hypothesis of Wendan Decoction treating Generalized Anxiety Disorder.

RRS. While in vitro, WDD can inhibit microglia activation from IL-6 stimulation. Taken together, the possible pharmacological mechanism of WDD against GAD is anti-inflammation mediated through IL-6.

Abbreviations

GAD, Generalized Anxiety Disorder; SSRIs, Serotonin Reuptake Inhibitor; SNRIs, Serotonin-norepinephrine reuptake Inhibitor; TCM, Traditional Chinese medicine; RCT, randomized controlled trials; WDD, Wendan Decoction; HAMA, Hamilton Anxiety Scale; SAS, Self-Rating Anxiety Scale; TCMSP, Traditional Chinese Medicine Systems Pharmacology database; ETCM, The Encyclopedia of Traditional Chinese Medicine database; UniProt, Unified Protein Database; OMIM, Online Mendelian Inheritance in Man database; NCA, network topology analysis; BC, Betweenness Centrality; CC, Closeness Centrality; DC, Degree Centrality; EC, Eigenvector Centrality; HRP, horseradish peroxidase; LC-MS, liquid chromatography tandem mass spectrometry; ReSpect, RIKEN MSn spectral database for phytochemicals; GNPS, Global Natural Products Social Molecular Networking; SPF, Specific Pathogen Free; RRS, repeated restraint stress; ELISA, Enzyme-linked immunosorbent assay; WB, western blot; OFT, Open field test; EPM, elevated plus maze; OD, optical density; BCA, bicinchoninic acid; DEX, Dexamethasone.

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Disclosure

All authors declare no conflict of interest.

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