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Effectiveness of different exercise interventions on depressive symptoms among college students: a network meta-analysis

Yang Xiao[1,2†], Chaofan Shi[1*†], Xiaotian Zhang[1] and Haitao Liu[1,3*]

Abstract

Background Depression affects approximately 25% of college students globally. Physical exercise shows promise as a low-cost, high-adherence intervention for depression, but research comparing different exercise types is lacking. This study aims to evaluate the efficacy of various exercise interventions in alleviating depressive symptoms among college students through a network meta-analysis, to inform targeted exercise prescriptions.

Methods We conducted a systematic search of six databases (PubMed, Web of Science, Cochrane Library, EMBASE, SCOPUS, and ScienceDirect) from their inception to July 1, 2024. Interventions were classified into six categories based on exercise type and intensity. Data extraction and systematic analysis were performed using Review Manager 5.4. A network meta-analysis was conducted using Stata 14.0, with heterogeneity assessed via node-splitting models, and results presented as standardized mean differences (SMD) and 95% confidence intervals (CI).

Results Forty-two randomized controlled trials involving 1,169 participants were included. The network meta-analysis revealed that Special Training Unit (STU), Dynamic Resistance Movement Group (DRMG), and Aerobic Exercise Group (AEG) demonstrated high effectiveness in improving depressive symptoms. STU showed the highest probability of being the most effective intervention (65.1%), followed by DRMG (64.8%), AEG (61.3%), and Strength and Resistance Training Group (SRTG) (60.9%). High-Intensity Training Group (HITG) (26.2%) and Moderate Intensity Group (MIG) (21.7%) showed less impact on improving depressive symptoms. The limited effectiveness of HITG may relate to excessive physiological stress responses, while MIG potentially provided insufficient stimulation to trigger optimal neurobiological adaptations for mood improvement.

Conclusions Special Training Units (STU) and Dance and Rhythmic Movement Group (DRMG) interventions demonstrate superior efficacy in reducing depressive symptoms among college students. These findings suggest that integrating rhythmic movement with psychological components may offer optimal benefits compared to intensity-focused exercise approaches, providing evidence-based guidance for mental health programs in university settings.

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Keywords Physical exercise, College students, Depressive symptoms, Intervention effectiveness, Network meta-analysis

Introduction

Depression is one of the most prevalent mental health disorders globally, affecting individuals across all age groups. Its core symptoms include low mood, loss of interest, and reduced energy, significantly impacting patients' physical and mental well-being [1]. The World Health Organization (WHO) reports that approximately 3.8% of the global population is affected by depression, including 5.0% of adults and 5.7% of those aged 60 and above [2]. Research indicates a particularly high prevalence of depressive symptoms among college students, with an estimated 25% experiencing depression or depressive symptoms worldwide [3]. College students suffering from depression often experience a substantial decrease in quality of life, with notable effects on their academic performance, social interactions, and family relationships [4]. If left unaddressed, these depressive symptoms can escalate into more severe depressive disorders. Over the past few decades, the proportion of individuals experiencing depressive symptoms has increased significantly [5]. While traditional antidepressant medications can effectively modulate brain neurotransmitters to achieve therapeutic effects, long-term use may lead to drug dependence and withdrawal reactions. In contrast, physical exercise has emerged as a promising intervention that not only enhances physical health but also ameliorates depressive symptoms [6]. Compared to pharmacological and psychological therapies, exercise interventions offer advantages such as lower costs and better adherence, establishing themselves as an important non-pharmacological approach to treating depression [7].

Current research on the effects of physical exercise in alleviating depressive symptoms has made significant progress. Recent findings have advanced our understanding of the neurobiological effects of exercise on depression. Rahmani (2022) demonstrated that unique neural activation patterns may underlie the variability in clinical responses to exercise interventions [8]. By integrating these insights with existing literature, researchers can achieve a more nuanced understanding of the mechanisms and effectiveness of exercise-based interventions for depression, particularly among young adults. However, most studies focus primarily on clinical efficacy, often neglecting the underlying mechanisms through which different exercise regimens modulate depression [9]. For instance, Jiang et al. found that exercise can significantly reduce depressive symptoms, with varying effects depending on the type, intensity, and frequency of the exercise [10]. Some researchers suggest that specialized training may be particularly effective in treating depressive symptoms [11]. Zhang et al. demonstrated that traditional Chinese Qigong-based exercises can effectively lower depression levels in college students by improving the flow of qi and blood through the meridians [12]. Moreover, Babiss et al. reported that college students who regularly engage in physical exercise exhibit significantly lower self-reported depressive symptoms compared to their less active counterparts [13]. Numerous studies indicate that physical exercise offers a cost-effective approach to improving depressive symptoms [14–15].

Given the current state of research, existing systematic reviews and meta-analyses predominantly focus on single-effect interventions, such as moderate-intensity aerobic exercise or high-intensity aerobic exercise, on depressive symptoms in college students. There is a lack of comparative studies examining the effects of different types of physical exercise, which limits the selection and optimization of intervention strategies in clinical practice [16–17]. This network meta-analysis addresses this research gap by directly comparing the relative efficacy of multiple exercise interventions for depressive symptoms in college students. Therefore, this study aims to employ a network meta-analysis to explore recent randomized controlled trials investigating the effects and mechanisms of various exercise interventions on depressive symptoms in college students. Compared to traditional pairwise meta-analysis, network meta-analysis offers the distinct advantage of simultaneously comparing multiple interventions and generating hierarchical rankings of effectiveness, even when direct comparisons between certain interventions are lacking in the literature. By systematically collecting and analyzing research on different types of physical exercise for depression in college students, we seek to comprehensively evaluate the antidepressant effects of various exercise regimens. Through comparing and ranking different exercise interventions, we aim to identify the most effective approaches for alleviating depressive symptoms in college students. This ranking will provide a foundation for future research into the specific neurobiological mechanisms underlying these effects and inform more targeted intervention strategies.

Methods

Literature search strategy

This systematic review and meta-analysis protocol was prospectively registered in the International Prospective Register of Systematic Reviews (PROSPERO) database (registration number: CRD420251027876). The study was conducted and reported in accordance with

the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement. We conducted computerized searches in PubMed, Web of Science, Cochrane Library, and EMBASE databases from their inception to July 1, 2024. To expand the scope of the literature search, we also searched SCOPUS, ScienceDirect, CNKI, China National Knowledge Infrastructure, VIP, and Wanfang databases. The English search strategy combined MeSH terms and free-text words: (("physical activity" OR "exercise" OR "physical training" OR "sport") AND ("college student" OR "undergraduate" OR "university student") AND ("depression" OR "depressive disorder" OR "depressive mood")). We referred to the Medical Subject Headings vocabulary to standardize search term combinations. Synonyms were used to expand the search of subject terms and improve retrieval rates. For Chinese databases, we employed a search strategy combining subject terms and free-text words in Chinese.

To further expand literature sources, we manually screened reference lists of all relevant meta-analyses and systematic reviews to supplement additional eligible studies that may have been missed in the database searches. Language was restricted to English and Chinese, with no publication year limitations. For Chinese databases (CNKI, Wanfang), we utilized the Chinese Biomedical Literature Database (CBM) standardized medical terminology correspondences to ensure accurate term matching. Searches were conducted by bilingual researchers with expertise in both languages and in exercise science to ensure comprehensiveness and appropriate context interpretation. All searches were completed in July 2024, with no restrictions on publication status. Researchers were assigned to conduct initial screening for different databases to identify eligible literature. To ensure screening accuracy, all initially screened literature underwent two independent full-text screenings by two reviewers. In cases of disagreement, a third reviewer was consulted to reach consensus. All included studies underwent a rigorous quality assessment process. First, two researchers independently assessed the risk of bias for each randomized controlled trial using the Cochrane Collaboration's risk assessment tool. The two researchers cross-checked their assessment results, with a third reviewer consulted in case of discrepancies. The data extraction process defined each variable in detail: demographic characteristics included sample size, mean age, and gender composition; intervention protocols included specific exercise types, intensity levels, weekly frequency, duration per session, and total intervention period; depression assessment used relevant rating scales or indicators. These variables were summarized in the data extraction table for subsequent meta-analysis.

Data and methods

Inclusion criteria

(1) Study participants were full-time college students aged 18–30 years, with no history of severe physical or mental illness.
(2) Intervention measures included aerobic or resistance exercises for the experimental group, while the control group did not engage in any form of physical exercise.
(3) Study design was a randomized controlled trial (RCT) with a detailed description of randomization methods, implementation of blinding and allocation concealment, and reporting of dropouts and loss to follow-up.
(4) Primary outcome measures included scores from standard depression assessment scales such as the Self-Rating Depression Scale (SDS) and Center for Epidemiologic Studies Depression Scale (CES-D). Secondary outcome measures included scores from other depression assessment scales like the Hamilton Depression Rating Scale (HAMD) and Beck Depression Inventory (BDI).
(5) Reported sample sizes for each group, means and standard deviations of depression scale scores, 95% confidence intervals, and effect sizes suitable for network meta-analysis.

Exclusion criteria

(1) Studies not involving full-time college students aged 18–30 years.
(2) Intervention measures not including aerobic or resistance exercise programs.
(3) Participants with a history of physical or mental illness severely affecting their health.
(4) Non-randomized controlled trials, studies with unclear randomization methods, or those not employing blinding.
(5) Outcome measures not including standard depression assessment scales or using non-standard self-developed scales.
(6) Incomplete analyzable data, such as missing sample sizes, means, or standard deviations for each group.
(7) Literature with duplicated or fraudulent data.
(8) Studies with significant differences in participant compliance or high dropout rates.

Literature screening and data extraction

Two researchers independently reviewed the literature and extracted data based on the inclusion and exclusion criteria. Disagreements or inconsistencies between researchers were resolved through discussion with a third researcher. The following data were extracted from

the 42 randomized controlled trials: first author's name, publication year, country, exercise content, outcome measures, intervention duration, sample size, effect size with its standard error and 95% CI, and the mean values and standard deviations of variables for both control and intervention groups. For missing data, we first contacted the original authors for supplementary information. If no response was received, studies with missing outcome data essential for effect size calculation were excluded from the analysis. Missing non-critical data (such as exact intervention duration) were coded as 'NA' in our extraction table and noted in the limitations.

Quality assessment of included studies

The quality of the included RCTs was assessed using Review Manager 5.4 provided by Cochrane. The 31 included studies were scored according to the following criteria: "+" was rated as low risk of bias, indicating that study methods met quality standards and results were reliable; "?" represented unclear risk, indicating insufficient information to make a judgment; and "-" indicated high risk of bias, suggesting significant methodological flaws that might affect result reliability. Studies receiving 6 to 7 "+" were classified as low risk of bias, those with 4 to 5 "+" were considered moderate risk, and those with 4 or fewer "+" were deemed high risk of bias. Assessment items included random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, selective reporting, and other sources of bias.

Statistical analysis

This study used sample size-weighted means to calculate pooled standard deviations, accounting for differences in sample sizes across studies and improving estimation precision. The standardized mean difference (SMD) was used as the effect size measure.

The SMD calculation formula is:

$$SMD = \frac{\left(\overline{X}1 - \overline{X}2\right)}{Spooled}$$

Where $\bar{X}1$ and $\bar{X}2$ represent the mean effects for the experimental and control groups, respectively, and Spooled is the pooled within-group standard deviation. SMDs for each study were calculated based on the reported means and standard deviations of depression scores for experimental and control groups. These calculations facilitated subsequent heterogeneity tests, publication bias assessments, and pooled effect size computations.

Heterogeneity assessment

Heterogeneity Assessment Heterogeneity among studies was assessed using Q-test and I^2 statistics. The Q-test, based on the weighted sum of squared differences between individual study effects and the pooled effect, is calculated as:

$$Q = \sum wi(Ti - T)^2$$

Where wi is the study weight, Ti is the individual study effect, and T is the pooled effect. A Q value greater than its degrees of freedom indicates significant heterogeneity. The I^2 statistic directly reflects the inconsistency of effect sizes across studies, providing a comprehensive assessment of heterogeneity. It is calculated as:

$$I^2 = \frac{(Q - df)}{Q}$$

I^2 values of 25%, 50%, and 75% represent low, moderate, and high heterogeneity, respectively. A fixed-effects model was employed when $I^2<50\%$ and $P>0.1$; a random-effects model was used when $I^2\geq50\%$ or $P\leq0.1$. For high heterogeneity ($I^2>75\%$), we conducted subgroup and sensitivity analyses to explore sources of heterogeneity.

Pooled effect size calculation

Following heterogeneity assessment, a random-effects model was employed to calculate the weighted average of study effect sizes, yielding the final pooled effect size. This approach mitigates random errors from individual studies, providing a reasonable estimate of the overall effect and a more accurate assessment of the intervention effect of physical exercise on depression in college students.

The pooled effect size is calculated as:

$$T = \frac{\sum(wiTi)}{\sum wi}$$

Where wi is the study weight and Ti is the individual study effect size. This weighted average considers factors such as sample size and variance, resulting in a more accurate and reliable pooled effect size.

Results

Literature screening process and outcomes

The initial search yielded 4,275 articles relevant to the research topic. After preliminary screening of titles and abstracts, 1,908 articles were selected for full-text review. Following the exclusion of studies that did not meet the criteria, 31 articles were ultimately included, encompassing a total of 1,169 participants (Fig. 1).

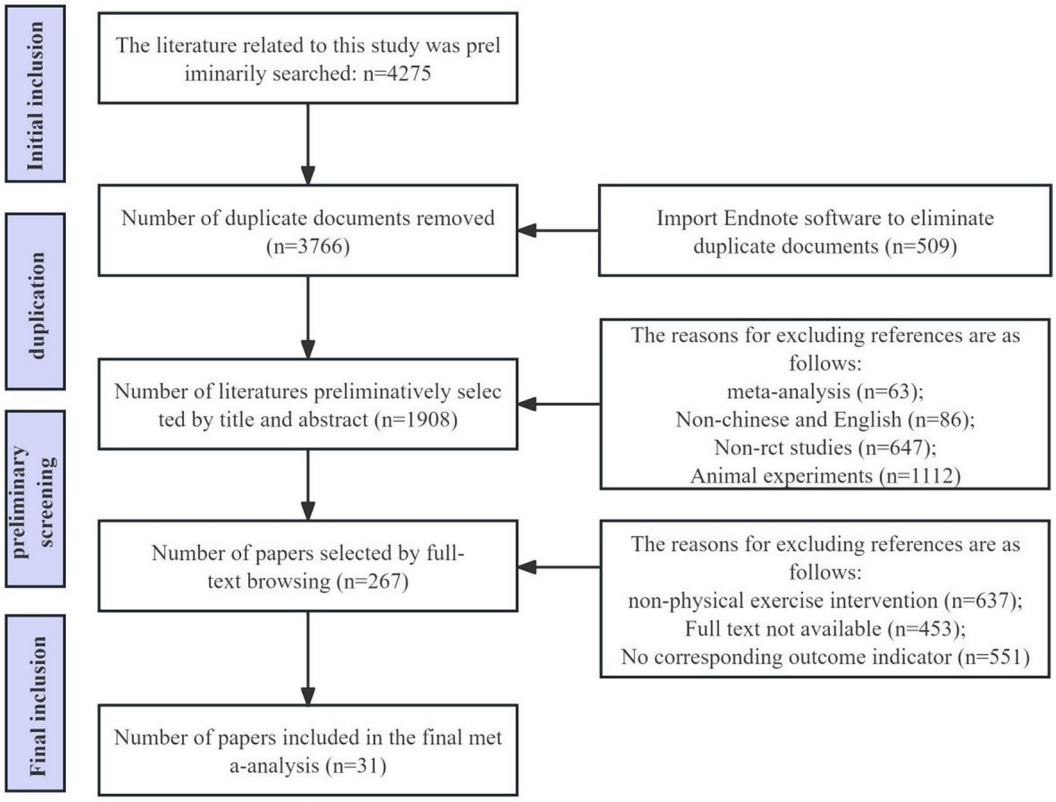

Fig. 1 Literature screening flow chart

Characteristics of included studies

The review included 31 randomized controlled trials (RCTs) involving 1,169 college students. Interventions were classified based on exercise type and intensity, comprising: aerobic exercise (e.g., jogging, brisk walking, yoga, dance), dance and rhythmic movements (e.g., Baduanjin, Five Animals Play, fitness qigong, Daoyin health-preservation exercises, Long Fist), moderate-intensity exercise (e.g., basketball, badminton, aerobics, middle-distance running), strength and resistance training (e.g., bodybuilding, Pilates), high-intensity training (e.g., high-intensity interval training [HIIT]), and special training (including psychological interventions such as behavioral activation therapy).

These classifications considered the comprehensive physiological and psychological impact mechanisms of different exercise regimens, resulting in six intervention categories: Aerobic Exercise Group (AEG), Dance and Rhythmic Movement Group (DRMG), Moderate Intensity Exercise Group (MIG), Strength and Resistance Training Group (SRTG), High Intensity Training Group (HITG), and Special Training Unit (STU). The basic characteristics of the included studies are presented in Table 1.

In the network of these six interventions, lines between nodes indicate direct comparative evidence between two interventions, line thickness represents the number of studies comparing two treatments, and node size indicates the total sample size for each intervention. Closed loops were formed by comparisons between MIG-DRMG, MIG-HITG, DRMG-HITG, DRMG-SRTG, AEG-STU, AEG-SRTG, AEG-DRMG, and AEG-HITG. Figure 2 illustrates the network diagram comparing outcomes across different intervention strategies.

Quality assessment of included studies

Two researchers independently evaluated the quality of included studies using Review Manager 5.4 software, following assessment criteria outlined in the Cochrane Handbook. The evaluation items included: (1) Random sequence generation: Low risk if appropriate randomization methods were used (e.g., computer-generated random numbers, random number tables); unclear risk if randomization methods were not described; high risk if non-random methods were used (e.g., allocation based on consultation order or birth date). (2) Allocation concealment: Low risk if appropriate concealment methods were used (e.g., central randomization, opaque envelopes); unclear risk if concealment methods were not described; high risk if non-concealment methods were used (e.g., open random allocation table). (3) Blinding of participants and personnel: Low risk if appropriate

Table 1 Basic characteristics of literature

First Author (Year)	Sample Size (T/C)	Age	Sports intervention characteristics				out-come
			content	cycle (month)	frequency (Times/week)	Duration (minutes/time)	
Asuman [18] (2020a)	29/35	18–25	Aerobic exercise group	Medium cycle	Medium frequency	NA	BDI
Asuman (2020b)	28/35	18–25	Dance and rhythmic movement group	Medium cycle	Medium frequency	NA	BDI
Zhao [19] (2023a)	29/28	18–25	Aerobic exercise group	Long cycle	Medium frequency	Medium length	SDS
Zhao (2023b)	29/28	18–25	Strength and resistance training group	Long cycle	Medium frequency	Medium length	SDS
JiangYH [20](2009b)	10/10	22	Aerobic exercise group	Medium cycle	Medium frequency	Short training	SCL-90
Jiang YH(2009a)	10/10	22	Dance and rhythmic movement group	Medium cycle	Medium frequency	Medium length	SCL-90
Ma MK [21](2017a)	31/31	18–22	Dance and rhythmic movement group	Medium cycle	Medium frequency	Medium length	SDS
Ma MK(2017b)	31/31	18–22	Moderate intensity exercise group	Medium cycle	Medium frequency	Medium length	SDS
Fu XY [22](2016b)	21/21	21 ± 1.1	Aerobic exercise group	Long cycle	low frequency	Long training	SCL-90
Fu XY(2016a)	21/21	21 ± 1.1	Dance and rhythmic movement group	Long cycle	low frequency	Long training	SCL-90
Emily [23](2018b)	18/18	18–30	Aerobic exercise group	Long cycle	Medium frequency	Short training	BDI
Emily(2018a)	19/18	18–30	High intensity training group	Long cycle	Medium frequency	Short training	BDI
Yin XW [24] (2007a)	7/8	18–22	Dance and rhythmic movement group	Medium cycle	low frequency	Medium length	SCL-90
Yin XW (2007b)	8/8	18–22	High intensity training group	Medium cycle	low frequency	Short training	SCL-90
Smits [25](2008a)	16/16	20.68	Aerobic exercise group	short cycle	low frequency	Short training	BDI
Smits (2008b)	14/16	20.68	Special training unit	short cycle	low frequency	Short training	BDI
Li [26](2014a)	15/15	20.6	Strength and resistance training group	Medium cycle	Medium frequency	Medium length	CES-D
Li(2014b)	15/15	20.6	Special training unit	Medium cycle	Medium frequency	Medium length	CES-D
He [27](2004a)	30/30	18–20	Dance and rhythmic movement group	Long cycle	Medium frequency	Medium length	SDS
He(2004b)	30/30	18–20	Strength and resistance training group	Long cycle	Medium frequency	Medium length	SDS
Khirollah [28](2016a)	16/14	20.99	Aerobic exercise group	Medium cycle	NA	Medium length	depres-sion
Khirollah(2016b)	16/14	20.99	Special training unit	Medium cycle	NA	Medium length	depres-sion
Chen LH [29](2016)	60/60	18–22	Dance and rhythmic movement group	Medium cycle	low frequency	Medium length	SCL-90
Liao M [30](2006)	60/60	18–22	Dance and rhythmic movement group	Long cycle	High frequency	Medium length	SCL-90
Li HY [31](2009)	35/35	21.1 ± 0.87	Moderate intensity exercise group	Long cycle	Medium frequency	Medium length	SCL-90
Wu YJ [32](2019)	51/51	18.24	Dance and rhythmic movement group	Medium cycle	High frequency	Medium length	SCL-90
Fu FX [33](2019)	80/80	19.81 ± 1.04	Dance and rhythmic movement group	Long cycle	low frequency	Long training	SCL-90
Tian [34](2012)	30/30	18–22	Dance and rhythmic movement group	Medium cycle	Medium frequency	Long training	SCL-90
Bargı[35](2021)	15/16	20 ± 1.07	Aerobic exercise group	short cycle	High frequency	Medium length	BDI

Table 1 (continued)

First Author (Year)	Sample Size (T/C)	Age	Sports intervention characteristics				out-come
			content	cycle (month)	frequency (Times/week)	Duration (minutes/time)	
Gai-Neng Mo [36] (2013)	60/60	17–25	Dance and rhythmic movement group	Long cycle	Medium frequency	Medium length	SCL-90
Jiao X [37](2021)	40/40	18–22	Dance and rhythmic movement group	Long cycle	High frequency	Long training	SCL-90
GUO [38](2021)	30/30	18–22	Dance and rhythmic movement group	Medium cycle	Medium frequency	Medium length	SCL-90
Ma [38](2017)	31/31	18–22	Dance and rhythmic movement group	Medium cycle	Medium frequency	Medium length	SDS
Ke [40](2019)	20/17	19.4 ± 0.5	Dance and rhythmic movement group	Medium cycle	High frequency	NA	SDS
Luo [41](2021)	157/158	18.58 ± 2.25	Dance and rhythmic movement group	Long cycle	Medium frequency	Short training	SDS
Wang B [42](2021)	100/100	19–21	Dance and rhythmic movement group	Long cycle	Medium frequency	Long training	SCL-90
ZhaoXD [43](2018)	30/30	19.35 ± 0.68	Aerobic exercise group	Medium cycle	Medium frequency	Medium length	SCL- 90
Lin JF [44](2020)	50/50	18–22	Dance and rhythmic movement group	Long cycle	Medium frequency	Short training	SCL-90
Zhou Y [45](2015)	25/25	18—24	Aerobic exercise group	Long cycle	High frequency	Medium length	SDS
Zhang YZ [46](2021)	30/30	19–22	Aerobic exercise group	Medium cycle	Medium frequency	Long training	SDS
Chen JX [47](2019)	18/18	18–22	Dance and rhythmic movement group	Long cycle	Medium frequency	Medium length	CES-D
Falsafi [48](2016)	23/23	18–22	Dance and rhythmic movement group	short cycle	High frequency	Short training	BDI

Note: (1)Aerobic exercise group - AEG、(2)Dance and rhythmic movement group-DRMG、(3)Moderate intensity exercise group - MIG、(4)Strength and resistance training group - SRTG、(5)High intensity training group - HITG、(6)Special training unit - STU

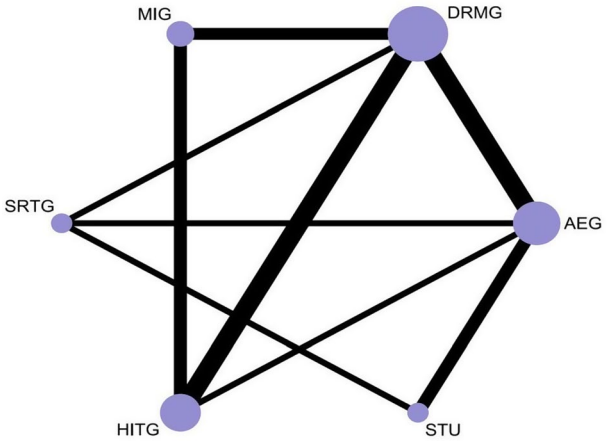

Fig. 2 Networks for multiple treatment comparisons Note: (1)Aerobic exercise group - AEG、(2)Dance and rhythmic movement group-DRMG、(3) Moderate intensity exercise group - MIG、(4)Strength and resistance training group - SRTG、(5)High intensity training group - HITG、(6)Special training unit - STU

blinding was used (e.g., placebo control); unclear risk if blinding was not described; high risk if blinding was not used. (4) Blinding of outcome assessment: Low risk if outcome measurement used blinding; unclear risk if blinding was not described; high risk if outcome measurement did not use blinding. (5) Incomplete outcome data: Low risk if follow-up completion rate was ≥ 80% or if appropriate methods were used to handle missing data; unclear risk if missing data were not described; high risk if follow-up completion rate was < 80% and missing data were not addressed. (6) Selective reporting: Low risk if pre-registered protocols matched reported results; unclear risk if no pre-registered protocol existed; high risk if reported results were inconsistent with pre-registered protocols. (7) Other bias: Low risk if no other apparent sources of bias existed; unclear risk if potential sources of bias were uncertain; high risk if other apparent sources of bias existed (e.g., baseline imbalance, protocol violations). The two researchers cross-checked their assessment results, with disagreements resolved through third-party arbitration.

The summarized quality assessment results for all studies are presented in a risk of bias assessment graph (Fig. 3), visually displaying the bias status of each study. The distribution of various types of bias across studies is shown in Fig. 4. The assessment process emphasized standardization and objectivity of results, providing high-quality evidence support for subsequent research.

Fig. 3 Assessment of the risk of bias for included studies. +, low bias risk; -, high bias risk;? unclear bias risk

Effects of different physical exercises on depression in college students

Overall inconsistency test results

Overall Inconsistency Test Results: We conducted global inconsistency analysis using the node-splitting model, which evaluates the internal consistency of network meta-analysis by comparing differences between direct and indirect evidence. In network meta-analysis, a P-value greater than 0.05 in this test indicates no statistically significant inconsistency between direct comparisons (from head-to-head studies) and indirect comparisons (derived from the network), supporting the validity of combining these different sources of evidence. Results showed (Table 2) that different physical exercises formed good closed loops for interventions on depression in college students. All pairwise comparisons had $P > 0.05$, indicating good internal consistency and model stability. Specifically: AEG vs. DRMG ($P = 0.67$), AEG vs. SRTG ($P = 0.47$), AEG vs. HITG ($P = 0.65$), AEG vs. STU ($P = 0.54$), DRMG vs. MIG ($P = 0.51$), DRMG vs. SRTG ($P = 0.89$), DRMG vs. HITG ($P = 0.65$), MIG vs. SRTG ($P = 0.51$), SRTG vs. STU ($P = 0.54$). This suggests good internal consistency in pairwise comparisons without local inconsistency, supporting the use of a consistency model for network meta-analysis.

Network Meta-Analysis results under the consistency model

This study included four closed loops: MIG-DRMG-AEG-HITG-MIG; MIG-DRMG-AEG-STU-HITG-MIG; SRTG-DRMG-AEG-STU-HITG-SRTG; and SRTG-DRMG-AEG-HITG-SRTG, each containing four or five edges. Consistency analysis of outcome indicators showed $P > 0.05$ for all loops, with 95% CI including 0. Differences between other interventions were not statistically significant, indicating good consistency among included studies.

Ranking of network meta-analysis results

SUCRA rankings represent the probability of being the best and second-best interventions (Table 3). Combining SUCRA assessment results, the interventions were probabilistically ranked. The potentially most effective intervention was STU (65.1%), which may be related to its comprehensive approach combining psychological behavioral activation with physical activity, simultaneously improving physiological and psychological states. This was followed by DRMG (64.8%), whose rhythmic movements may improve mood through enhanced body awareness and mindfulness; AEG (61.3%), which operates by improving cardiopulmonary function and promoting neurotransmitter secretion; and SRTG (60.9%), which may improve depressive states by enhancing self-efficacy and body image. HITG (26.2%) and MIG (21.7%) showed the lowest effectiveness, possibly due to stress

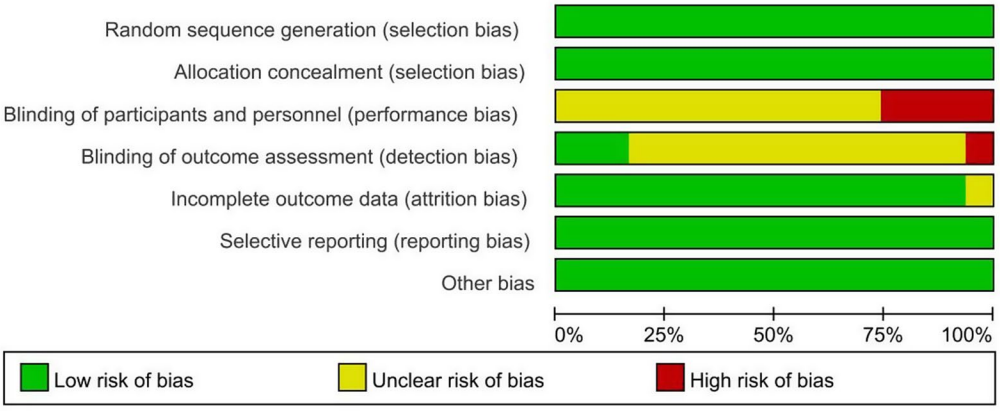

Fig. 4 Distribution of studies across the bias ranking for each type of bias

Table 2 Local inconsistency check

Treatments	Direct effect		Indirect effect		Overall		*P*-value
	Coef.	Std.Err	Coef.	Std.Err	Coef.	Std.Err	
A, B	-0.37	1.42	0.88	2.46	-1.23	2.85	0.67
A, D	1.85	3.11	-0.89	2.10	2.74	3.76	0.47
A, E	2.80	3.36	1.07	1.85	1.73	3.84	0.65
A, F	-0.96	2.13	1.50	3.38	-2.46	4.00	0.54
B, C	2.23	1.64	-1.10	4.76	3.33	5.04	0.51
B, D	-2.00	2.40	0.29	2.70	-0.49	3.62	0.89
B, E	1.31	1.34	3.03	3.60	-1.73	3.84	0.65
C, E	2.41	1.63	-3.33	4.77	3.33	5.04	0.51
D, F	0.89	2.70	-1.57	2.95	2.46	4.00	0.54

Note: (1)A - Aerobic exercise group - AEG、(2)B - Dance and rhythmic movement group-DRMG、(3)C - Moderate intensity exercise group - MIG、(4)D - Strength and resistance training group - SRTG、(5)E - High intensity training group - HITG、(6)F - Special training unit - STU

Table 3 SUCRA numerical ranking of the effects of different physical exercises on depression of college students

Rank	Intervening measure	SUCRA
1	Special training unit(STU)	0.651
2	Dance and rhythmic movement group(DRMG)	0.648
3	Aerobic exercise group(AEG)	0.613
4	Strength and resistance training group(SRTG)	0.609
5	High intensity training group(HITG)	0.262
6	Moderate intensity exercise group(MIG)	0.217

Note: (1)Aerobic exercise group - AEG、(2)Dance and rhythmic movement group-DRMG、(3)Moderate intensity exercise group - MIG、(4)Strength and resistance training group - SRTG、(5)High intensity training group - HITG、(6) Special training unit - STU

responses induced by high-intensity exercise and insufficient physiological stimulation at moderate intensity to achieve optimal antidepressant effects. Thus, STU and DRMG interventions may be most effective for college students with depressive symptoms (Fig. 5).

Pairwise Meta-Analysis and publication Bias test results

This study included six pairwise comparisons. Results of the pairwise meta-analysis are shown in Table 4. Compared to the control group, most studies showed high heterogeneity (> 50%). This heterogeneity may stem from multiple factors: (1) differences in participant characteristics, such as depression severity, comorbid conditions, and baseline fitness levels; (2) heterogeneity in intervention protocols, including variations in specific exercise types, intensity, frequency, and duration; (3) differences in outcome assessment tools, with various depression scales having different sensitivities and specificities. To assess result robustness, we conducted sensitivity analyses by sequentially excluding each study, which confirmed that the main findings remained stable. The comparison results suggest that STU may be superior to other interventions. Publication bias analysis showed that the funnel plot was generally symmetrical around the zero line, with all literature distributed near the central axis and roughly symmetrical on both sides, indicating a low possibility of publication bias or small-sample effects (Fig. 6).

Discussion

This network meta-analysis evaluated the efficacy of various physical exercise interventions on depressive symptoms among college students. The results indicate that STU, DRMG, AEG, and SRTG demonstrate high effectiveness in alleviating depressive symptoms in this

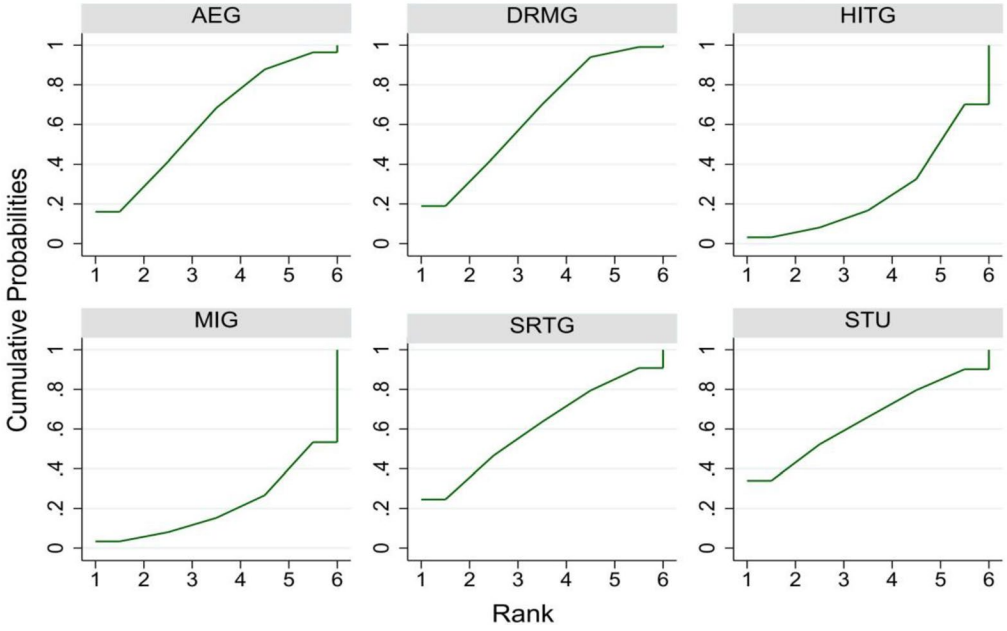

Fig. 5 Rank probabilities for efficacy

Table 4 Comparative ranking table of various exercise interventions on direct and network effects

DRMG					
0.23 (-3.67,4.13)	STU				
-0.04 (-2.34,2.26)	-0.27 (-3.72,3.19)	AEG			
-0.00 (-3.35,3.35)	-0.23 (-4.04,3.58)	0.04 (-3.31,3.39)	SRTG		
-1.51 (-3.90,0.88)	-1.73 (-6.18,2.71)	-1.47 (-4.57,1.63)	-1.51 (-5.53,2.52)	HITG	
-1.86 (-4.84,1.11)	-2.09 (-6.93,2.75)	-1.82 (-5.49,1.84)	-1.86 (-6.30,2.58)	-0.35 (-3.32,2.61)	MIG

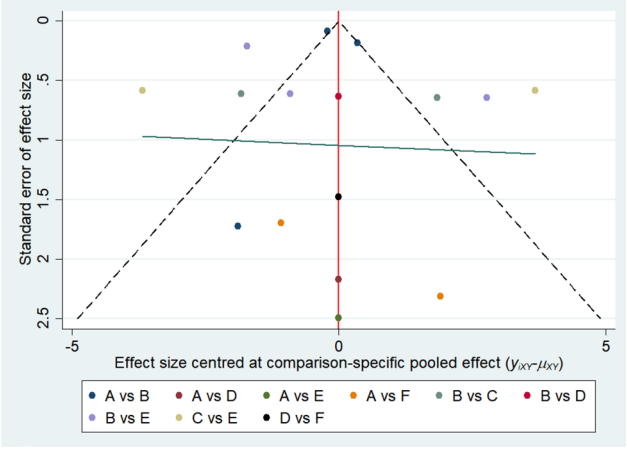

Fig. 6 Egger method tests publication bias Note: (1)A - Aerobic exercise group - AEG、(2)B - Dance and rhythmic movement group-DRMG、(3)C - Moderate intensity exercise group - MIG、(4)D - Strength and resistance training group - SRTG、(5)E - High intensity training group - HITG、(6)F - Special training unit - STU

population. These findings not only provide a basis for developing targeted intervention strategies but also open new avenues for exploring the molecular mechanisms underlying exercise-induced improvements in depressive mood.

STU showed the most significant effect in improving depressive symptoms among college students, potentially operating through multiple molecular mechanisms. Firstly, STU may enhance neuroplasticity by upregulating brain-derived neurotrophic factor (BDNF) expression. BDNF, through its receptor TrkB, activates downstream signaling pathways such as PI3K/Akt and MAPK/ERK, promoting neuronal survival and synaptic plasticity [49]. This mechanism involves the phosphorylation of cAMP response element-binding protein (CREB), which regulates the expression of antidepressant genes like VGF and Arc. Secondly, STU may ameliorate depressive symptoms by modulating monoamine neurotransmitter systems. It may enhance serotonin (5-HT) synthesis by increasing tryptophan hydroxylase (TPH) activity while potentially increasing synaptic 5-HT concentrations by downregulating serotonin transporter (SERT) expression [50]. Additionally, STU may promote dopamine (DA) and norepinephrine (NE) synthesis by increasing tyrosine hydroxylase (TH) activity. Furthermore, STU may improve depressive symptoms by regulating the hypothalamic-pituitary-adrenal (HPA) axis function, involving modulation of glucocorticoid receptor (GR) expression and function. This includes promoting GR nuclear translocation and DNA binding capacity to enhance negative feedback regulation of cortisol, thereby reducing HPA axis hyperactivation [51]. This process may involve regulation of chaperone proteins such as heat shock protein 90 (HSP90) and FK506 binding protein 51 (FKBP51). Lastly, STU may alleviate depressive mood by modulating inflammatory responses, primarily through inhibition of the nuclear factor κB (NF-κB) signaling pathway, reducing pro-inflammatory cytokine production (e.g., IL-6, TNF-α, IL-1β), while promoting anti-inflammatory cytokine IL-10 expression through activation of peroxisome proliferator-activated receptor γ (PPARγ) [52].

The second-ranked intervention, DRMG, showed significant effectiveness in improving depressive symptoms among college students, aligning with findings by Gordon et al. [53] (2018). DRMG may influence brain function by stimulating muscle cells to secrete specific myokines. For instance, exercise-induced IL-6 may promote BDNF expression by activating the JAK/STAT3 signaling pathway [54]. Another myokine, irisin, may improve cognitive function and emotional state by upregulating hippocampal BDNF expression. Additionally, DRMG might affect brain function by enhancing insulin sensitivity and glucose metabolism, involving the activation of AMP-activated protein kinase (AMPK) and peroxisome proliferator-activated receptor γ coactivator 1α (PGC-1α) signaling pathways, thereby improving mitochondrial function and energy metabolism. Furthermore, DRMG may reduce oxidative stress-induced neuronal damage by upregulating antioxidant enzyme systems, such as superoxide dismutase (SOD), glutathione peroxidase (GPx), and catalase (CAT) [55].

AEG, ranked third, showed efficacy in alleviating depressive symptoms, though less pronounced than STU and DRMG. AEG may induce feelings of pleasure and analgesia by increasing β-endorphin release, activating μ-opioid receptors. This process involves the activation of dopaminergic neurons in the ventral tegmental area (VTA), influencing the function of the nucleus accumbens and prefrontal cortex [56]. Additionally, AEG may promote neural stem cell proliferation and differentiation by increasing Wnt signaling pathway activity, involving β-catenin nuclear translocation and TCF/LEF transcription factor activation, thus enhancing the expression of hippocampal neurogenesis-related genes. Moreover, AEG may promote neurogenesis and angiogenesis by upregulating vascular endothelial growth factor (VEGF) and insulin-like growth factor 1 (IGF-1) expression. In terms of epigenetic regulation, AEG may facilitate BDNF expression by reducing DNA methylation levels in the BDNF promoter region and modulate antidepressant gene expression by influencing the activity of histone acetyltransferases (HATs) and deacetylases (HDACs) [57].

SRTG, ranked fourth, showed efficacy in alleviating depressive symptoms, though less pronounced than STU, DRMG, and AEG. SRTG may increase the synthesis and release of 5-HT, NE, and DA by upregulating monoamine oxidase (MAO) expression, potentially

involving the activation of CREB and BDNF signaling pathways. Simultaneously, SRTG may induce feelings of pleasure and analgesia by increasing β-endorphin release and activating μ-opioid receptors, possibly involving the activation of mesolimbic dopaminergic neurons [58]. Furthermore, SRTG may promote hippocampal neurogenesis by enhancing neural stem cell proliferation and differentiation through increased Wnt signaling pathway activity [59]. This may be associated with the upregulation of growth factors such as VEGF and IGF-1.

Notably, the high-intensity interval training group (HITG) and moderate-intensity exercise group (MIG) showed relatively weaker effects in this study, which may be related to several potential negative mechanisms. Firstly, high-intensity exercise may lead to excessive reactive oxygen species (ROS) production, overwhelming the antioxidant system's capacity and resulting in dysfunction of mitochondrial electron transport chain complexes I and III, thereby affecting ATP production and cellular energy metabolism [60]. This oxidative stress state may exert neurotoxic effects on neurons and increase neuroinflammation, which is associated with worsening depressive symptoms. Research by Schuch et al. (2016) indicates that excessive exercise may lead to increased oxidative stress marker levels, positively correlated with worsening depressive symptoms [61]. Secondly, prolonged high-intensity exercise may cause HPA axis hyperactivation, leading to sustained increases in cortisol secretion. This may affect GR downregulation and dysfunction through epigenetic modifications (such as increased DNA methylation in the GR gene promoter region), thus impacting stress response regulation. This mechanism is supported by recent research from Hird et al., who found that excessive high-intensity exercise can disrupt glucocorticoid receptor sensitivity and HPA axis function in ways that may exacerbate rather than ameliorate depressive symptoms [62]. Additionally, excessive exercise may lead to downregulation of dopamine D2 receptors, causing neuroadaptive changes similar to addictive behaviors, possibly involving the accumulation of ΔFosB transcription factor and affecting the expression of related genes [63]. In contrast, the poor performance of the moderate-intensity exercise group may be related to insufficient stimulus intensity, failing to trigger necessary neurobiological adaptations such as increased BDNF secretion and monoamine neurotransmitter regulation. Recent research by Kandola et al. and Herold et al. suggests individuals with depression may require personalized exercise intensity within an optimal window-sufficient to trigger neuroplastic adaptations but not so intense as to produce adverse stress responses [64–65].

These findings provide crucial molecular mechanistic evidence for developing safe and effective exercise intervention programs while highlighting the complexity of selecting appropriate exercise types and intensities. Comprehensive analysis indicates that effective exercise interventions may improve depressive symptoms through multiple parallel and interacting pathways: (1) neuroplasticity pathways: upregulating BDNF and its downstream signaling (PI3K/Akt and MAPK/ERK), promoting neuronal survival and synaptic plasticity; (2) neurotransmitter regulation: enhancing 5-HT, NE, and DA synthesis and utilization, improving synaptic transmission; (3) neuroendocrine regulation: optimizing HPA axis function, enhancing glucocorticoid receptor sensitivity, improving stress response; (4) anti-inflammatory effects: inhibiting pro-inflammatory cytokine production through NF-κB signaling pathway; (5) metabolic regulation: improving glucose utilization and mitochondrial function, enhancing energy metabolism; (6) epigenetic regulation: modulating gene expression through DNA methylation and histone modifications. These mechanisms do not act in isolation but form a complex regulatory network, synergistically improving neural system function and emotional regulation. Future research should further elucidate these molecular mechanisms, explore the impact of different exercise regimens on specific neurotransmitter systems and signaling pathways, and investigate how these mechanisms operate at the individual level. This will contribute to the development of more precise and personalized exercise intervention programs, thereby enhancing the therapeutic efficacy for depressive symptoms in college students.

In conclusion, this study underscores the importance of exercise as a potential adjunctive treatment for depressive symptoms while highlighting the complexity of considering exercise type and intensity when formulating intervention strategies. Notably, while this study primarily focuses on physiological and molecular mechanisms, the onset and progression of depression are often also significantly influenced by psychosocial factors. Future research should explore integrated interventions under the biopsychosocial model, combining exercise with psychosocial approaches such as cognitive-behavioral therapy, interpersonal therapy, or social support. This integrated approach may produce synergistic effects, further enhancing intervention efficacy. For instance, group exercises may enhance the psychological benefits of exercise alone by increasing social connection and reducing loneliness. Meanwhile, psychoeducation may enhance patients' awareness of exercise benefits, increasing adherence and long-term effects. Future research should focus on basic research into these mechanisms, exploring the impact of different exercise regimens on specific neurotransmitter systems and signaling pathways, and investigating how these mechanisms operate at the individual level.

Limitations

This study has several limitations: (1) Significant heterogeneity exists among the included studies, particularly in demographic characteristics, specific physical exercise protocols, and choice of assessment indicators. This heterogeneity may affect result generalizability, as different populations (such as different gender proportions, age ranges, or depression severity) may respond differently to the same interventions. For example, some studies included students with mild depressive symptoms, while others included those with moderate to severe symptoms, potentially leading to differences in intervention effects. (2) The included studies only involved short-term interventions, lacking long-term follow-up data. It is unclear whether these intervention effects can be sustained or whether there are long-term benefits. Future research should include follow-up periods of at least 6–12 months. (3) Most included studies utilized subjective scales to assess patients' cognitive function and daily living abilities, lacking objective neuroimaging and biomarker indicators. This limits our understanding of the mechanisms by which interventions work at the biological level. Integrating functional magnetic resonance imaging (fMRI) or electroencephalogram (EEG) data would enhance the reliability of mechanism explanations. (4) The study did not thoroughly explore the specific mechanisms and comparative advantages of different types of physical exercises; future research should design more refined experiments directly comparing the effects of different exercise modalities on specific neurobiological markers.

Conclusion

This network meta-analysis confirms the effectiveness of various exercise interventions in alleviating depressive symptoms among college students, providing crucial evidence for developing targeted exercise intervention strategies. Our findings suggest that comprehensive exercise programs, particularly those incorporating STU and DRMG, may be the most effective strategies for improving depressive symptoms in college students. These results can be directly applied to clinical practice in university mental health services, formulating personalized intervention plans for students with depressive symptoms. Specifically, university counseling centers could develop structured programs containing special training units (such as combining physical activity with cognitive behavioral techniques) or offer dance and rhythmic movement courses based on traditional Eastern body-regulating methods (such as qigong, tai chi). These programs can be adjusted according to students' initial depression severity, preferences, and physical health status, enhancing intervention effectiveness and adherence. Additionally, these interventions can be integrated into existing university health promotion frameworks, such as part of freshman orientation health programs or as strategies for managing stress during examination periods. This approach of translating research findings into practical applications can enhance the comprehensiveness and effectiveness of mental health services for college students.

However, given the limitations of this study, these findings warrant further validation through additional high-quality randomized controlled trials. Future research should focus on: (1) exploring the specific effects of STU and DRMG on depressive symptoms of varying severity; (2) designing long-term follow-up studies (≥ 12 months) to assess the durability of intervention effects; (3) integrating objective neurobiological indicators (such as serum BDNF levels, inflammatory markers, electroencephalography, or functional magnetic resonance imaging) to assess mechanisms; (4) exploring the synergistic effects of multimodal interventions (such as exercise + cognitive behavioral therapy); (5) developing and validating customized intervention plans for specific populations (such as students with comorbid anxiety disorders or trauma history). These research directions will provide more comprehensive guidance for managing depressive symptoms in college students and optimizing mental health service resource allocation.

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Author contributions

X and S contributed equally to this work and share first authorship. X conceived and designed the study, and was responsible for overall direction and planning. X and S implemented the research, conducted data analysis, and drafted the manuscript. L and Z participated in the interpretation of the results, L critically revised the manuscript for important intellectual content, and approved the final version to be published. All the authors reviewed the manuscript.

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Data availability

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

Declarations

Ethics approval and consent to participate

Not applicable, as this study is a systematic review of published literature and does not involve human subjects or animal experiments.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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