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Expanding Horizons – A Broad-Spectrum Review of Emerging Medical Applications of N-Acetylcysteine

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Abstract:

N-acetyl-l-cysteine is a thiol-containing compound widely recognized for its antioxidant, mucolytic, and glutathione-replenishing properties. Historically established for use in acetaminophen toxicity and respiratory diseases, n-acetyl-l-cysteine has garnered growing interest for its broad therapeutic potential across diverse medical domains. This narrative review synthesizes evidence from meta-analyses published from January 2024 onwards,

sourced from PubMed, to present emerging clinical applications of n-acetyl-l-cysteine. Findings suggest promising roles for n-acetyl-l-cysteine as an adjunctive therapy in managing rheumatoid arthritis, improving reproductive outcomes in women with polycystic ovary syndrome, and enhancing recovery following physical exertion by reducing oxidative stress and inflammation. While results for substance use disorders remain mixed, n-acetyl-l-cysteine's modulation of glutamatergic and antioxidant pathways warrants further investigation. Nonetheless, n-acetyl-l-cysteine's favorable safety profile and multifaceted biological actions underscore its potential in various clinical contexts. This review highlights medical areas of growing evidence on n-acetyl-l-cysteine's efficacy while identifying gaps that necessitate further well-designed trials. Its aim is to inform about new research directions.

Keywords: N-acetylcysteine, N-acetyl-l-cysteine, Rheumatoid Arthritis, Polycystic ovary syndrome, physical exertion recovery

1. Introduction

N-acetyl-l-cysteine (NAC) has become a compound of undeniable clinical importance. It is stocked in virtually every hospital and is the most popular antioxidant used in laboratory experiments (Herzenberg, 2019; Suzuki, 2009). It is also commercially very popular, sold as an over-the-counter supplement in pharmacies, health food stores, and online platforms in many countries including the United States, Canada, and Australia (Šalamon et al., 2019).

Its story starts in the second half of the 20th century. Patented in 1960, NAC was first brought to the market three years later in September of 1963 after FDA approval (Schwalfenberg et al., 2021; Kobylarz et al., 2023). NAC has two main areas with historically most established clinical utility: first as an effective mucolytic agent, employed since 1969 in conditions such as cystic fibrosis and chronic obstructive pulmonary disease, then since 1977 as the antidote for acetaminophen (paracetamol) overdose, where it leverages its ability to replenish hepatic glutathione (Schwalfenberg et al., 2021; Syiem et al., 2024; Tieu et al., 2023). The profound impact of NAC in mitigating acetaminophen-induced liver injury further led to its global recognition culminating in its inclusion on the World Health Organization's (WHO) Model List of Essential Medicines (Šalamon et al., 2019).

Chemically NAC is a sulfhydryl-containing N-acetylated derivative of the amino acid L-cysteine (Tenório et al., 2021). While its precursor L-cysteine can be found in abundance in foods such as meat, grains, and dairy, NAC itself exists in nature only in trace amounts inside some fruits and vegetables, such as asparagus or tomatoes (Mokhtari et al., 2017; Demirkol et al., 2004).

Its current fundamental medical significance stems from its role as a precursor to L-cysteine, which is crucial for the synthesis of intracellular glutathione, the body's primary endogenous antioxidant (Atkuri et al., 2007). NAC also directly exerts antioxidant effects by scavenging reactive oxygen species (ROS) via its free thiol group and can act as a disulfide-breaking agent (Kalyanaraman, 2022). Despite having historically well-established applications, there is a rapidly increasing interest in exploring new therapeutic applications for NAC, driven by a deeper understanding of its diverse mechanisms of action beyond simple antioxidant and mucolytic effects (Pedre et al., 2021). These include modulation of inflammatory pathways, regulation of glutamatergic neurotransmission, neurotrophic effects, and potential benefits in conditions involving mitochondrial dysfunction (Tardiolo et al., 2018; Xiao et al., 2016; Ooi et al., 2018) The compound's favorable safety profile, general tolerability even at high doses, and cost-effectiveness further encourage its investigation as an adjunctive or primary therapy across a wide spectrum of medical conditions (Tenório et al., 2021; Ooi et al., 2018; Joshy et al., 2023)

This review aims to synthesize and critically evaluate the current clinical evidence supporting emerging uses of NAC. The significance of this review lies in providing a holistic overview of NAC’s clinical potential. By identifying existing knowledge gaps, and highlighting areas in need for further investigation, this work seeks to inform readers about potential future research directions and pave the way for broader clinical understanding of this versatile compound.

2. Research materials and methods

A comprehensive narrative review was conducted by searching PubMed for meta-analytical studies on NAC published between January 1, 2024, and May 10, 2025. The search strategy used terms including "N-acetylcysteine," "NAC," "meta-analysis," and "systematic review," with filters applied for English language and human studies. Inclusion criteria were meta-analyses and systematic reviews with quantitative synthesis evaluating NAC in human subjects across various clinical indications. Titles and abstracts were screened independently with full texts assessed for eligibility. Data extracted from eligible studies included study

design, number of participants, NAC dosing and administration (if mentioned), interventions, outcomes measured, and key results. The synthesis focused on summarizing the main findings of the meta-analyses, providing an overview of NAC's therapeutic potential across diverse health conditions.

3. Research results

3.1. NAC in substance use disorders

The meta-analysis by Winterlind et al. (2024) evaluated the efficacy of NAC in reducing cravings among individuals with substance use disorders. The study addressed inconsistencies in prior findings (Greenberg et al. 2022; Winterlind et al., 2024). Winterlind et al. (2024) identified nine randomized controlled trials (RCTs) which assesed NAC in 623 participants addicted to various substances. The duration of the analysed studies ranged from 3 days to 12 weeks. The cravings were measured via self-report tools (see Table 1). Some trials included behavioral or psychosocial co-interventions (see Table 2). Pooled results showed no significant reduction in cravings with NAC versus placebo (SMD = 0.189, 95% CI = −0.015 to 0.393) (Winterlind et al., 2024). These findings differ from earlier meta-analyses that reported significant effects (Chang et al., 2021; Duailibi et al., 2017; Winterlind et al., 2024). The reason for that might be due to the fact that the meta-analysis by Winterlind et al. (2024) included additional, more recent, larger trials. However, the authors underline that there are still some limitations, which include small number of trials analyzed, high heterogeneity across trials (I2 = 99.26%), potential variability in NAC product quality and focus only on assessing craving. In order to draw definitive conclusions, further research on NAC in substance use disorders should assess broader clinical outcomes, such as abstinence and relapse (Winterlind et al., 2024).

Table 1. Summary of trials included in meta-analysis by Winterlind et al. (2024).

Study (first author, year)	Substance(s)	Baseline (N=NAC/N=Placebo	Craving Measure(s)
Schmaal et al. (2011)	Tobacco	10/12	QSU-B (subscales and total score)
Yoon (2013)	Alcohol	22/24	PACS, OCDS (total scores)
Roten et al. (2013)	Cannabis	45/44	MCQ-SF (subscales and total score)
Back et al. (2016)	Multiple	13/14	VAS (three subscales)
Schulte et al. (2017)	Tobacco	24/24	QSU, VAS (total scores)
Back et al. (2021)	Multiple	49/41	OCDS (total score)
McKetin et al. (2021)	METH	76/77	CEQ (total score)
Back et al. (2023)	Alcohol	93/89	OCDS (two subscales)
Morley et al. (2023)	Alcohol	21/21	PACS (total score)

CEQ – Craving Experiences Questionnaire, **MCQ-SF** – Marijuana Craving Questionnaire – Short Form, **METH** – Methamphetamine, **NAC** – N-acetylcysteine, **OCDS** – Obsessive Compulsive Drinking Scale, **PACS** – Penn Alcohol Craving Scale, **QSU-B** – Questionnaire of Smoking Urges – Brief, **VAS** – Visual Analogue Scale

Source: Data from Winterlind et al. (2024).

Table 2. Summary of interventions applied in trials included in meta-analysis by Winterlind et al. (2024).

Study (first author, year)	NAC dosage	Co-Intervention in study and placebo groups
Schmaal et al. (2011)	3 days 1800 mg 2x/day and 1 day 1800 mg 1x/day	None reported
Yoon (2013)	900 mg/day x 1 week; 1800 mg/day x 1 week, 2,700 mg/day x 1 week; 3,600 mg/day x 5 weeks	None reported
Roten et al. (2013)	2400 mg/day x 8 weeks	Contingency management + cessation counseling x 8 weeks
Back et al. (2016)	2400 mg/day x 8 weeks	CBT x 8 weeks
Schulte et al. (2017)	2400 mg/day x 2 weeks	None reported
Back et al. (2021)	2400 mg/day x 8 weeks	CBT x 8 weeks
McKetin et al. (2021)	2400 mg/day x 12 weeks	None reported
Back et al. (2023)	2400 mg/day x 12 weeks	CBT x 12 weeks
Morley et al. (2023)	2400 mg/day x 4 weeks	None reported
second trial; **CBT** – Cognitive Behavioral Therapy		

Source: Data from Winterlind et al. (2024).

3.2. NAC in physical excertion

NAC is considered to show prominent results in reducing fatigue and muscle damage caused by physical exertion (Sadowski et al., 2024; Sakelliou et al., 2016; Kerksick et al., 2010; Michailidis et al., 2013; Cobley et al., 2011).

The systematic review and meta-analysis by Sadowski et al. (2024) evaluated the effects of NAC on biomarkers of oxidative stress, inflammation, lactate metabolism, and muscle damage after exercise (Sadowski et al., 2024). The summary of the analysed studies is depicted in Table 3 below. The study analysed twenty RCTs involving a total of 266 healthy adults. It examined oral or intravenous NAC supplementation. Intervention durations ranged from 3 to 30 days. NAC significantly increased reduced glutathione levels ($p < 0.00001$), reduced lipid peroxidation measured by thiobarbituric acid reactive substances ($p = 0.02$) and decreased inflammatory interleukin-6 ($p = 0.03$). It also lowered post-exercise blood lactate ($p = 0.03$), muscle soreness twenty-four hours post-exercise ($p = 0.001$) and muscle soreness

after exercise, regardless of the time ($p = 0.03$). No significant changes were found in oxidized glutathione, tumor necrosis factor-alpha and creatine kinase (Sadowski et al., 2024).

According to the recent meta-analysis, NAC seems to enhance antioxidant capacity, reduce inflammatory and fatigue-related biomarkers, and support recovery post-exercise (Sadowski et al., 2024) which is not in line with the previous findings that NAC did not prove to be beneficial for sports performance (Rhodes & Braakhuis 2017). However, the previous meta-analysis focused on performance and side effects of NAC supplementation, rather than specifically on the biomarker outcomes in response to physical exertion like the newest meta-analysis by Sadowski et al., 2024. Nevertheless, there are still some limitations to the study by Sadowski et al. (2024) which include small sample sizes, limited search databases, heterogeneity in participant training levels, inability to differentiate effects by exercise type (aerobic vs. anaerobic), lack of studies on immune response, missing 72-hour comparative data, and diversity in biological materials used across studies (Sadowski et al., 2024).

Table 3. Summary of trials included in systematic review and meta-analysis by Sadowski et al. (2024).

Study (first author, year)	Sample size (n)	NAC dose & schedule; duration	Measured outcomes
Bailey et al. (2011)	8	IV 125 mg/kg b.w./h for 15 min before exercise, 25 mg/kg b.w./h throughout exercise; acute	Lactate
Christensen et al. (2019)	11	Oral 20 mg/kg b.w.; acute before excersise	Lactate
Cobley et al. (2011)	12	Oral 2 × 50 mg/kg b.w; chronic for 6 days + pre-exercise bolus.	CK, Muscle soreness
Ferreira et al. (2011)	17	Study 1 – Oral 2 × 300 or 2 × 600 mg (9 or 18 mg/kg b.w.); acute Study 2 – Oral 35, 70, or 140 mg/kg b.w.; acute	GSH, GSSG
Kelly et al. (2009)	9	Oral 1 800 mg, acute: 45 min before exercise	GSH, Lactate
Kerksick et al. (2010)	30	Oral 1 800 mg; chronic for 14 days	CK, TNF-α, Muscle soreness
Leelarungrayub et al. (2011)	29	Oral 2 × 600 mg day; chronic for 7 days	Lactate, TNF-α, CK
Medved et al. (2004)	8	IV 125 mg/kg b.w./h for 15 min, 25 mg/kg/h for 20 min prior to and throughout exercise; acute	GSH, GSSG
Merry et al. (2010)	9	IV 125 mg/kg/h for15 min, then 25 mg/kg/h for 20 min prior to and throughout exercise;	GSH, GSSG, Lactate

		acute	
Michailidis et al. (2013)	10	Oral 20 mg/kg b.w.; chronic for 7 days after training	GSH, GSSG, TBARS, IL-6, TNF-α, CK, Muscle soreness
Moraes et al. (2018)	20	Oral 2 × 600 mg/day; chronic for 7 days	GSH, TBARS, CK
Nielsen et al (2001)	19	Oral 6 g/day; chronic for 3 days before exercise	GSH, Lactate
Paschalis et al. (2018)	36	Oral 2 × 600 mg/day; chronic for 30 days	GSH
Rhodes et al. (2019)	17	Oral 1 g/day; chronic for 6 days	Muscle soreness
Sakelliou et al. (2016)	10	Oral 20 mg/kg/day; chronic for 8 days	GSH, GSSG, TBARS, IL-6, CK, Muscle soreness
Sen et al. (1994)	9	Oral 4 × 200 mg/day; chronic for 3 days	GSH, GSSG, TBARS
Silva et al. (2008)	29	Oral NAC (10 mg/kg b.w.) for 21 days or NAC plus placebo (14-day NAC + 7-day placebo); chronic	TNF-α, Muscle soreness
Slattery et al. (2014)	8	Oral 2 × 600 mg/day; chronic for 9 days	GSH, GSSG, TBARS, IL-6
Trewin et al. (2013)	9	Oral 5 × 100 mg/kg; acute: before excersise	GSH, GSSG, TBARS, Lactate
Trewin et al. (2015)	7	IV Initial loading dose of 62.5 mg/kg/h for the first 15 min, followed by a constant infusion of 25 mg/kg/h for the next 80 min; acute	GSH, GSSG, IL-6
b.w.– body weight; **CK** – creatine kinase; **GSH** – reduced glutathione; **GSSG** – oxidized glutathione; **IL-6** – interleukin-6; **IV** – intravenous; **NAC** – N-acetylcysteine; **TBARS** – thiobarbituric acid reactive substances.			

Source: Data from Sadowski et al. (2024).

3.3. NAC in Rheumatoid arthritis

Rheumatoid arthritis (RA) is a chronic autoimmune disease driven by inflammation and oxidative stres (Han et al., 2024; He et al., 2024). Despite standard disease-modifying antirheumatic drugs (DMARDs) therapy, some patients do not respond sufficiently to the first-line treatment (Hofman et al., 2025; He et al., 2024). Since NAC exhibits antioxidant and anti-inflammatory properties, it has been proposed as a potential adjunct therapy in RA (He et al., 2024).

The recent systematic review and meta-analysis by He et al. (2024) included four RCTs comparing NAC plus DMARDs to placebo plus DMARDs. The total number of participants

from analyzed RCTs was 204, all in active state of disease. Outcomes analyzed included disease activity, measured by DAS28-ESR and global health; number of tender and swollen joints; inflammatory markers, including ESR and CRP; oxidative stress (TAC, MDA, NO); and adverse events (He et al., 2024). The summary of the analysed trials is depicted in Table 4 below.

NAC significantly improved global health scores ($p = 0.03$), and reduced ESR ($p = 0.02$), CRP ($p = 0.03$), number of tender joints ($p = 0.03$) and swollen joints ($p = 0.003$). However, it did not significantly reduce disease activity or affect oxidative stress markers (all $p > 0.05$). Adverse effects were mild and comparable between groups, indicating good tolerability (He et al., 2024).

The meta-analysis by He et al. (2024) suggested that NAC's potential benefits in RA appear to be driven by anti-inflammatory rather than antioxidant mechanisms. Despite promising effects, the authors reported limitations that include small sample size and uniform dosing (He et al., 2024).

Table 4. Summary of trials included in systematic review and meta-analysis by He et al. (2024).

Study (first author, year)	Sample Size (N=NAC/N=Placebo)	Study duration	NAC Dosage	Measured outcomes
Batooei et al. (2018)	27/24	12 weeks	600 mg 2x/day	DAS28-ESR, Global Health, number of tender joints, number of swollen joints, ESR
Hashemi et al. (2019)	23/19	12 weeks	600 mg 2x/day	ESR, CRP, TAC, MDA, NO
Jamali et al. (2021)	22/19	8 weeks	600 mg 2x/day	DAS28-ESR, Global Health, number of tender joints, number of swollen joints, ESR
Esalatmanesh et al. (2022)	34/36	3 months	600 mg 2x/day	DAS28-ESR, ESR, CRP, TAC, MDA, NO
CRP – C-reactive protein; **DAS28-ESR** – Disease Activity Score 28 - erythrocyte sedimentation rate; **ESR** – erythrocyte sedimentation rate; **GH** – Global Health; **MDA** – malondialdehyde; **NAC** – N-acetylcysteine; **NO** – nitric oxide; **TAC** – total antioxidant capacity				

Source: Data from He et al. (2024).

3.4. NAC in polycystic ovary syndrome

Polycystic ovary syndrome (PCOS) is an endocrine disorder characterized by hormonal imbalance, insulin resistance, and infertility (Dilliyappan et al., 2024; Viña et al., 2025). The management of PCOS is challenging due to its complex pathogenesis. Letrozol, lomiphene citrate (CC) and metformin are the drugs that were suggested for managing infertility in women with PCOS. However, the results, especially concerning CC and metformin, are inconclusive (Sharpe et al., 2019; Hoeger et al., 2021).

The recent systematic review and meta-analysis by Viña et al. (2025) assessed NAC as a potential therapy for infertility in women with PCOS. Twenty-two studies, including eighteen RCTs, with a total of 2,515 participants were analyzed. The meta-analysis did not present the information on dosages of NAC and duration of the trials. The trials compared NAC, alone or with clomiphene citrate (CC), letrozole, or laparoscopic ovarian drilling to different combinations of placebo, CC, metformin, l-carnitine, letrozole and laparoscopic ovarian drilling. Outcomes included levels of progesterone, LH, FSH, estradiol (E2), total testosterone (TT), sex hormon binding globulin (SHBG), endometrial thickness, and follicle count (Viña et al., 2025). The summary of the analysed trials is depicted in Table 5 below.

NAC significantly increased progesterone levels ($p=0.02$) and endometrial thickness ($p=0.02$) compared to the placebo and other interventions. The study reported also an increase in LH compared to metformin ($p=0.003$). No significant effects were found for FSH, E2, TT, or SHBG. NAC showed trends toward improving follicle count, but results were inconsistent. Limitations of the study include: high heterogeneity, small number of studies for some outcomes, and publication bias which was assesed only through visual inspection (Viña et al., 2025).

According to the meta-analysis, NAC, due to its antioxidant and insulin-sensitizing properties, may be a valuable adjunctive therapy, particularly for women with thin endometrium or low progesterone levels (Viña et al., 2025). This study strengthens the findings from previous meta-analysis that NAC may be an alternative supplement instead of metformin in women with PCOS (Song et al., 2020).

Table 5. Summary of trials included in systematic review and meta-analysis by Viña et al. (2025).

Study (first author, year)	Study design	Intervention	Sample size (N)
Mostajeran et al., 2018	RCT	Letrozole + NAC	65
		Letrozole + placebo	61
Nasr et al., 2010	RCT	LOD + NAC	30
		LOD + placebo	30
Badawy et al., 2007	Cross-over trial	CC + NAC	210
		CC	260
Köse et al., 2015	Clinical trial	PCOS + NAC	17
		PCOS	17
Oner et al., 2011	RCT	NAC	45
		Metformin	30
Kilic-Okman et al., 2004	Clinical trial	NAC	20
El Sharkwy et al., 2019	RCT	CC + NAC	82
		CC + l-carnitine	80
Cheraghi et al., 2016	RCT	NAC	15
		Placebo	15
Fulghesu et al., 2002	Prospective analysis	NAC	37
Maged et al., 2015	RCT	CC	40
		CC + NAC	40
Hashim et al., 2010	RCT	NAC + CC	95
		Metformin + CC	97
Rizk et al., 2005	RCT	NAC	75
		CC + placebo	75
Salehpour et al., 2012	RCT	CC + NAC	82
		CC + placebo	85
Javanmanesh et al., 2015	RCT	NAC	46
		Metformin	48
Ghomian et al., 2019	RCT	Clomiphene + NAC	33
		Clomiphene	33
Nemati et al., 2017	RCT	CC + NAC	54
		CC + Metformin	54
Elgindy et al., 2010	RCT	Long IVF protocol + NAC	38
		Long IVF protocol	38
Teimouri et al., 2021	RCT	Letrozole + NAC	158
		Letrozole	159
Gayatri et al., 2010	RCT	NAC	50
		Metformin	50

Chandil et al., 2019	RCT	NAC	45
		Metformin	45
Elnashar et al., 2007	RCT	NAC	30
		Metformin	31
Hassan et al., 2019	RCT	CC + NAC	150
		CC + placebo	150
CC – clomiphene citrate; **LOD** – laparoscopic ovarian drilling; **NAC** – N-acetyl-cysteine; **RCT** – randomised controlled trial			

Source: Data from Viña et al. (2025) and Ghomian et al. (2019).

4. Discussion

The compiled meta-analyses on NAC across various conditions highlight its broad therapeutic potential (see Table 6). NAC demonstrates promising effects in RA, PCOS and exercise-induced oxidative stress and fatigue (He et al., 2024; Viña et al., 2025; Sadowski et al., 2024).

In the context of substance addiction, NAC's glutamatergic modulation and antioxidant properties were associated with reductions in cravings for different substances (Winterlind et al., 2024). While some meta-analyses reported a statistically significant reduction in cravings, others find no clear evidence for NAC's efficacy (Chang et al., 2021; Duailibi et al., 2017; Winterlind et al., 2024). The findings of NAC in substance use disorders remain insufficient and assessment of broader clinical outcomes is needed in order to draw definite conclusions (Winterlind et al., 2024).

Some studies suggest the possible utility of metformin in PCOS, but its role remains limited (Hoeger et al., 2021). Based on the meta-analytical findings by Viña et al. (2025), we suggest that in PCOS, NAC, an alternative to metformin, might be a valuable adjunctive therapy to letrozol, the drug that is currently considered the first-line treatment of infertility in PCOS (Song et al., 2020; Wang et al., 2019; Hoeger et al., 2021; Yifu, 2024).

Since NAC shows potential in reducing inflammatory mediators, possibly through mechanisms involving glutathione restoration and NF-κB inhibition (He et al., 2024; Verhasselt et al., 1999), it might be a valuable adjunct to DMARDs in RA (He et al., 2024).

In sport, NAC has been investigated for its role in mitigating exercise-induced oxidative damage and improving recovery (Devrim-Lanpir et al., 2021; Sadowski et al., 2024). Meta-analysis suggests that NAC supplementation can lower several biomarkers associated with exercise-induced oxidative stress and fatigue (Sadowski et al., 2024). Nevertheless, its effect on performance outcomes, such as time-to-exhaustion or peak power, appears minimal or

inconsistent (Rhodes & Braakhuis 2017). We suggest that future studies should focus on measuring both biomarkers and performance outcomes.

Across all studies, heterogeneity in study design—including NAC dosing, duration of supplementation, and outcome assessment methods—limits the ability to draw definitive conclusions. While meta-analyses attempt to account for this variability through subgroup and sensitivity analyses, the high heterogeneity values in several analyses underscore the need for more standardized, high-quality RCTs. Furthermore, while NAC's safety profile is generally favorable (Adil et al., 2018), many studies did not report adverse events systematically, leaving potential tolerability concerns underexplored.

Table 6. Summary of meta-analyses discussed in results.

Study	Utility of NAC analysed	Conclusions
Viña et al., 2025	Infertility in PCOS	Significant effect on progesterone, endometrial thickness and LH levels
Winterlind et al., 2024	Craving management for SUD	Limited impact on substance craving
He et al., 2024	RA	Reduction of inflammatory markers, improvement joint tenderness, and swelling
Sadowski et al., 2024	Reduction of fatigue and muscle damage caused by physical exertion	Promising results for reducing muscle soreness, lactate, TBARS and IL-6 concentrations and increasing GSH level following physical exertion
GSH – Glutathione; **IL-6** – Interleukin 6; **LH** – Luteinizing Hormone; **NAC** – N-Acetylcysteine; **PCOS** – Polycystic Ovary Syndrome; **RA** – Rheumatoid Arthritis; **SUD** – Substance Use Disorder; **TBARS** – Thiobarbituric Acid Reactive Substances		

Data from: (He et al., 2024; Viña et al., 2025; Sadowski et al., 2024; Winterlind et al., 2024).

5. Conclusions

In summary, meta-analytical evidence suggests that NAC, due to its antioxidant properties and modulation of inflammatory and neurotransmitter pathways, holds therapeutic promise across many different conditions. However, to establish its clinical utility more firmly, further research is needed -particularly large, well-designed randomized controlled trials with standardized dosing protocols, broader outcome measures, and robust reporting of clinical endpoints and adverse events.

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Artificial intelligence (AI) tools such as ChatGPT and ANARA were employed in this research solely to assist in refining the academic English language of the manuscript. Their purpose was to ensure clarity, consistency, and adherence to scientific writing standards. AI tools were used strictly for additional linguistic polishing-focused on proper grammar, style, and clarity of the text in presenting the results. Importantly, these tools were used only as support under the direct supervision of the authors. All final interpretations, classification of findings, and conclusions were determined exclusively by human experts with formal training in clinical medicine. The role of AI was limited to enhancing the efficiency of language refinement, pattern recognition, and data processing, and it did not replace human judgment in the analytical process.

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