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Comparative Impact of new intervention CSSSD versus Standard Lifestyle measures on Physiological Parameters, Psychosocial Well Being, and Academic Stress in adolescents with risk of metabolic syndrome: A Systematic Review

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Abstract

The increasing burden of metabolic syndrome among adolescents is largely attributed to the clustering of unhealthy lifestyle behaviors, including poor dietary habits, insufficient sleep, excessive screen exposure, and low levels of structured physical activity, all of which also influence psychosocial wellbeing and academic stress. Traditional lifestyle recommendations often target these factors in isolation, potentially limiting their overall effectiveness. This systematic review synthesizes existing evidence on an integrative lifestyle framework Cycling, Surya Namaskar (yoga), Sleep optimization, Screen-time regulation, and Dietary modification (CSSSD) to evaluate its potential effectiveness in improving Physiological Parameters, Psychosocial, and Academic-related outcomes among adolescents at risk of metabolic syndrome. A comprehensive search of PubMed, Scopus, and Web of Science was conducted for studies published between 2014 and 2025, yielding 32 eligible studies comprising randomized controlled trials, quasi-experimental studies, and observational designs involving adolescents aged 10–19 years. Study quality was appraised using the Cochrane RoB 2 tool and the Newcastle–Ottawa Scale, and findings were narratively synthesized due to substantial heterogeneity in interventions and outcome measures. The evidence indicates that sleep extension is consistently associated with improvements in insulin sensitivity and fasting glucose regulation, while yoga-based practices, including Surya Namaskar, demonstrate favorable effects on lipid profiles, blood glucose levels, and perceived stress scores. Structured cycling interventions show modest but clinically relevant reductions in body mass index and improvements in cardiorespiratory fitness, whereas high screen exposure is repeatedly associated with increased adiposity and elevated metabolic risk. Across studies, reductions in stress and improvements in quality of life are reported when lifestyle behaviors are modified; however, quantitative assessment of academic stress remains limited. Notably, no included study evaluated all five CSSSD components concurrently, and none comprehensively examined academic stress as a primary outcome. These findings highlight a substantial evidence gap and suggest that holistic, multi-component lifestyle interventions such as CSSSD may offer synergistic benefits beyond single-domain approaches. Future rigorously designed randomized controlled trials are required to test the combined CSSSD model, quantify effect sizes across metabolic and psychosocial endpoints, and explicitly evaluate academic stress outcomes in adolescents at metabolic risk.

Keywords: Adolescents; Metabolic syndrome; CSSSD, Surya Namaskar; Cycling; Sleep time; Screen time; Diet modification; Physiological Parameters, Psychosocial health; Academic stress.

Introduction

Metabolic risk among adolescents manifested through central obesity, dyslipidemia, insulin resistance, impaired glucose regulation, and elevated blood pressure has emerged as a major public health concern worldwide. Epidemiological evidence indicates a steady rise in the prevalence of metabolic syndrome during adolescence, a developmental period characterized by rapid physiological, psychological, and behavioral transitions (Alberti et al., 2005; Ford et al., 2008). These metabolic disturbances during youth are particularly concerning because they tend to track into adulthood, significantly increasing the lifetime risk of type 2 diabetes mellitus, cardiovascular disease, and premature morbidity.

Contemporary adolescent lifestyles are increasingly shaped by behavioral patterns that disrupt metabolic homeostasis. Insufficient sleep duration has been consistently identified as a critical determinant of insulin resistance and impaired glucose metabolism in youth. Experimental and observational studies demonstrate that even short-term sleep restriction can significantly reduce insulin sensitivity, alter hormonal regulation, and promote adiposity in adolescents (Klingenberg et al., 2013; Andrade et al., 2016; Dutil et al., 2023). Chronic sleep deprivation during adolescence often driven by academic pressures, social media use, and delayed circadian rhythms has been linked to heightened metabolic vulnerability (Chaput & Dutil, 2017; Owens, 2014).

Dietary behaviors further compound this risk. Increased consumption of ultra-processed foods, sugar-sweetened beverages, and unhealthy snacks has been associated with central adiposity and dyslipidemia, particularly when combined with sedentary screen-based behaviors (Schaan et al., 2019; World Health Organization [WHO], 2023). Adolescents with prolonged screen exposure often engage in mindless eating and reduced physical movement, creating a metabolic milieu conducive to weight gain and insulin resistance (Rey-López et al., 2008; Magister et al., 2025). Physical inactivity represents another critical contributor. Although school-based and community physical activity programs show benefits for cardiometabolic fitness, participation levels remain suboptimal, especially among urban adolescents (Singh et al., 2019; Hartwig et al., 2021). Aerobic activities such as cycling have demonstrated improvements in cardiometabolic risk profiles, including reductions in waist circumference and improvements in lipid parameters (Børrestad et al., 2012). However, declining active transport and increased reliance on digital entertainment continue to limit daily energy expenditure.

Beyond physiological consequences, metabolic risk in adolescence is closely intertwined with psychosocial functioning. Obese adolescents frequently experience emotional distress, poor self-esteem, peer victimization, and psychological strain, which may further disrupt health behaviors and stress-regulation pathways (Goodman & Goodman, 2009). These psychosocial stressors may indirectly exacerbate metabolic dysfunction through neuroendocrine mechanisms involving cortisol and inflammatory responses (Pascoe et al., 2020).

1.1 Rationale for an Integrative CSSSD Approach and the Need for Evidence Synthesis

Given the multifactorial origins of adolescent metabolic risk, interventions targeting single behaviors such as diet alone or exercise alone may be insufficient to generate sustained and meaningful health improvements. Adolescents live within interconnected behavioral ecosystems where sleep, diet, physical activity, screen exposure, and stress regulation continuously interact. Consequently, integrative lifestyle strategies may offer synergistic advantages over fragmented approaches.

Yoga-based practices, particularly Surya Namaskar, have gained attention as culturally adaptable, low-cost interventions with both physiological and psychological benefits. Evidence suggests that yoga can improve glucose metabolism, lipid profiles, autonomic balance, and stress regulation in adolescents (Saxena et al., 2012; Khalsa, 2004;

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Shindhe et al., 2021). Complementary findings indicate that pranayama and meditative components of yoga reduce cortisol levels and enhance emotional regulation, thereby addressing psychosocial stress pathways linked to metabolic dysfunction (Maheshkumar et al., 2022; Pascoe et al., 2020).

Similarly, aerobic activities such as cycling provide structured physical exertion that improves insulin sensitivity and cardiovascular fitness while being feasible within school and community settings (Børrestad et al., 2012). Sleep optimization represents another essential pillar, as adequate sleep duration and regular sleep timing are foundational for hormonal regulation, appetite control, and metabolic stability during adolescence (Chaput et al., 2016; Lam et al., 2019). National and international guidelines consistently emphasize sleep as a core determinant of adolescent health, yet it remains under-addressed in intervention research (Tremblay et al., 2016; National Sleep Foundation, 2015).

Screen-time regulation is equally critical. High recreational screen exposure has been associated with increased adiposity, insulin resistance, and psychological distress in adolescents (Liu et al., 2025; Rey-López et al., 2008). Importantly, evidence suggests that the metabolic impact of screen time may be amplified by concurrent unhealthy snacking patterns, underscoring the need for integrated behavioral modification (Schaan et al., 2019). Dietary improvements, aligned with WHO recommendations, further support metabolic health by reducing glycemic load and improving lipid balance (WHO, 2023).

Despite growing evidence supporting each of these components independently, existing research remains fragmented. Current trials tend to isolate yoga, physical activity, sleep, or screen behavior as standalone interventions, with limited exploration of combined, real-world lifestyle programs. Moreover, academic stress a salient concern during adolescence has received minimal attention in metabolic intervention studies, despite its known influence on sleep, mental health, and health behaviors (Wigfield & Eccles, 2000; Zimmerman & Arunkumar, 1994). Therefore, a comprehensive synthesis of available evidence is urgently needed to evaluate what is known about these lifestyle components, identify methodological and conceptual gaps, and inform the design of future combined-behavior trials. The Cycling, Surya Namaskar, Sleep optimization, Screen-time control, and Dietary modification (CSSSD) framework represents a holistic prevention model aligned with behavioral science principles and adolescent developmental needs (Michie et al., 2011; Durlak & DuPre, 2008). This review thus seeks to compare CSSSD-based approaches with standard lifestyle advice, evaluate metabolic and psychosocial outcomes, assess available evidence related to academic stress, and map priority areas for future rigorous intervention research.

1. Methods

This systematic review was designed and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure methodological rigor, transparency, and reproducibility.

2.1 Study Design and Framework

The review adopted a structured, protocol-driven approach consistent with PRISMA 2020 recommendations. A predefined search strategy, eligibility criteria, and outcome framework were established prior to study selection to minimize selection bias and enhance the reliability of the synthesis.

2.2 Eligibility Criteria

2.2.1 Population

Studies were eligible if they involved adolescents aged 10–19 years, irrespective of sex, socioeconomic background, or geographic setting. This age range was selected to align with the World Health Organization's definition of adolescence and to capture critical developmental stages associated with metabolic and behavioral risk transitions.

2.2.2 Publication Period

Only studies published between January 2014 and December 2025 were considered. This timeframe ensured inclusion of contemporary evidence reflecting recent advancements in lifestyle-based interventions and adolescent metabolic health research.

2.2.3 Study Designs

We included a broad range of empirical study designs to capture diverse forms of evidence, comprising randomized controlled trials, quasi-experimental intervention studies, prospective and retrospective

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cohort studies, and cross-sectional investigations. This inclusive approach was adopted due to the emerging nature of integrative lifestyle interventions in adolescent populations.

2.2.4 Intervention and Behavioral Components

Eligible studies were required to evaluate at least one of the following lifestyle or behavioral components:
(i) yoga-based practices, including Surya Namaskar;
(ii) cycling or other structured physical activity programs;
(iii) sleep duration or sleep quality interventions;
(iv) strategies aimed at reducing screen time or sedentary behavior; and
(v) dietary modification or nutrition-focused interventions.

Studies examining these components either independently or as part of a broader lifestyle strategy were included.

2.2.5 Outcome Measures

Studies were included if they reported outcomes in one or more of the following domains:

1. **Physiological outcomes**, such as body mass index, waist circumference, insulin resistance markers, lipid profiles, blood pressure, or glycemic indices;
2. **Psychosocial outcomes**, including perceived stress, self-esteem, emotional wellbeing, or quality of life;
3. **Academic-related outcomes**, such as academic stress, school functioning, or learning-related performance indicators.

2.3 Language and Accessibility

Only studies published in the English language with clearly reported and extractable outcome data were included to ensure consistency in interpretation and data synthesis.

2.4 Exclusion Criteria

Studies were excluded if they focused exclusively on adult populations, were case reports, editorials, commentaries, or narrative reviews, or lacked sufficient quantitative or qualitative outcome data relevant to the review objectives. Articles without accessible full texts or with non-extractable results were also excluded.

As shown in Figure 1, the evidence base of the review is composed of a diverse mix of study designs, reflecting both experimental rigor and real-world observational insights. Randomized controlled trials (RCTs) form the largest share, accounting for 36.4% of the included studies. This substantial proportion strengthens the internal validity of the review, as RCTs provide robust evidence on causal relationships between lifestyle interventions and metabolic, psychosocial, and academic outcomes. Cross-sectional studies represent the second-largest category at 30.3%, offering valuable snapshots of associations between lifestyle behaviors and health or academic indicators among adolescents. While these designs do not establish causality, they contribute important population-level insights and help identify emerging risk patterns.

Quasi-experimental studies constitute 18.2% of the evidence base, reflecting the practical challenges of implementing randomized designs in school- or community-based adolescent interventions. These studies provide meaningful intervention-related findings, particularly in real-world settings where randomization may not be feasible. Finally, cohort studies, comprising 15.2%, add a longitudinal perspective by tracking changes in metabolic and psychosocial parameters over time. Together, the balanced representation shown in Figure 1 underscores the methodological breadth of the included literature and supports a comprehensive understanding of integrative lifestyle interventions in adolescents.

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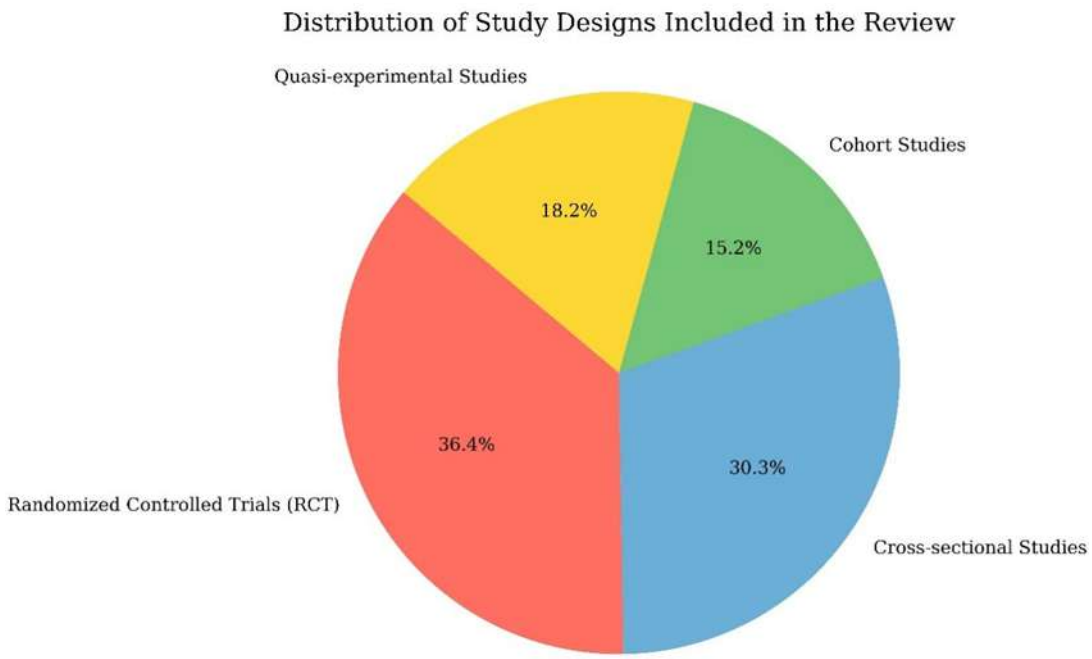
Figure 1 illustrates the proportional distribution of study designs included in the systematic review.



2.5 Search Strategy

A comprehensive and systematic literature search was conducted to identify relevant studies examining lifestyle-based interventions among adolescents at risk of metabolic syndrome. Three major electronic databases PubMed, Scopus, and Web of Science were searched to ensure broad coverage of biomedical, public health, and interdisciplinary research. The search strategy employed a combination of controlled vocabulary terms and free-text keywords related to the population, interventions, and outcomes of interest. Core search terms included "adolescents," "yoga," "Surya Namaskar," "sleep extension," "screen time," "diet intervention," "cycling," and "insulin resistance". Boolean operators (AND/OR) were used to refine and expand the search as appropriate. The search was limited to articles published between 2014 and 2025 to capture contemporary evidence reflecting recent lifestyle patterns and intervention approaches. In addition to database searches, the reference lists of all included articles and relevant review papers were manually screened to identify additional eligible studies that may not have been retrieved through electronic searches.

2.6 Study Selection

The study selection process followed a structured, multi-stage approach to minimize selection bias. Initially, two reviewers independently screened the titles and abstracts of all retrieved records to exclude clearly irrelevant studies. Full-text versions of potentially eligible articles were then obtained and assessed in detail against predefined inclusion and exclusion criteria. Eligible studies included randomized controlled trials, quasi-experimental studies, and observational designs involving adolescents aged 10–19 years that evaluated at least one lifestyle component relevant to the CSSSD framework. Any discrepancies between reviewers at either stage were discussed and resolved through mutual agreement. When consensus could not be reached, a third reviewer acted as an adjudicator to make the final decision, ensuring transparency and methodological rigor in the selection process.

2.7 Data Extraction

Data extraction was performed independently by two reviewers using a standardized data extraction form to ensure consistency and completeness. Extracted

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information included bibliographic details (author names and year of publication), country of study, sample size, participant age range, study design, characteristics of the intervention and comparison groups, duration of follow-up, and primary and secondary outcomes. Key findings related to physiological parameters (e.g., BMI, glucose, lipid profile, blood pressure), psychosocial outcomes, and academic or stress-related measures were recorded in detail. Information on study limitations, confounding factors, and adherence to interventions was also documented. Any inconsistencies in extracted data were cross-checked against the original articles and resolved through discussion.

2.9 Quality Assessment

The methodological quality and risk of bias of the included studies were systematically evaluated. Randomized controlled trials were appraised using the Cochrane Risk of Bias 2 (RoB 2) tool, which assesses bias across domains such as randomization, deviations from intended interventions, missing outcome data, outcome measurement, and selective reporting (Sterne et al., 2019). Observational studies were assessed using the Newcastle–Ottawa Scale, focusing on selection of participants, comparability of study groups, and outcome assessment (Wells et al., 2014). Quality assessments were conducted independently by two reviewers, with disagreements resolved through consensus to enhance reliability.

2.9 Data Synthesis

Given the substantial heterogeneity across included studies in terms of study design, intervention components, duration, and outcome measures, quantitative pooling of data was not appropriate. Therefore, a narrative synthesis approach was adopted. Findings were organized and synthesized thematically under each review objective, allowing comparison of patterns and consistencies across studies while accounting for methodological diversity. This approach facilitated a nuanced interpretation of evidence related to individual lifestyle components and highlighted gaps where integrated, multi-component interventions remain underexplored.

Figure 2 illustrates the distribution of the 32 included studies according to the primary lifestyle intervention examined. Dietary interventions represent the most frequently investigated domain, accounting for 12 studies, highlighting the dominant focus of existing research on nutritional modification in adolescent metabolic health. This is followed by yoga-based interventions (n = 10), including Surya Namaskar, reflecting growing interest in mind–body approaches for improving metabolic and psychosocial outcomes. Cycling and other structured physical activity interventions were represented in 7 studies, demonstrating moderate attention to aerobic exercise as a preventive strategy for obesity and metabolic syndrome. In contrast, sleep-focused interventions (n = 6) and screen-time reduction strategies (n = 5) were comparatively underrepresented, despite strong evidence linking sleep deprivation and excessive screen exposure with insulin resistance, adiposity, and psychosocial stress (Chaput et al., 2016; Tremblay et al., 2017). Importantly, Figure 2 reveals that most studies investigated single lifestyle components in isolation, rather than integrated or multi-component approaches. No study simultaneously examined all five domains diet, yoga, cycling, sleep optimization, and screen-time regulation underscoring a critical gap in the literature. This uneven distribution supports the rationale for proposing holistic frameworks such as the CSSSD model, which aligns with contemporary calls for systems-based lifestyle interventions in adolescent metabolic health (Sahoo et al., 2015). Overall, the pattern depicted in Figure 2 emphasizes the need to move beyond fragmented interventions toward comprehensive, integrative lifestyle strategies capable of addressing metabolic, psychosocial, and academic outcomes concurrently.

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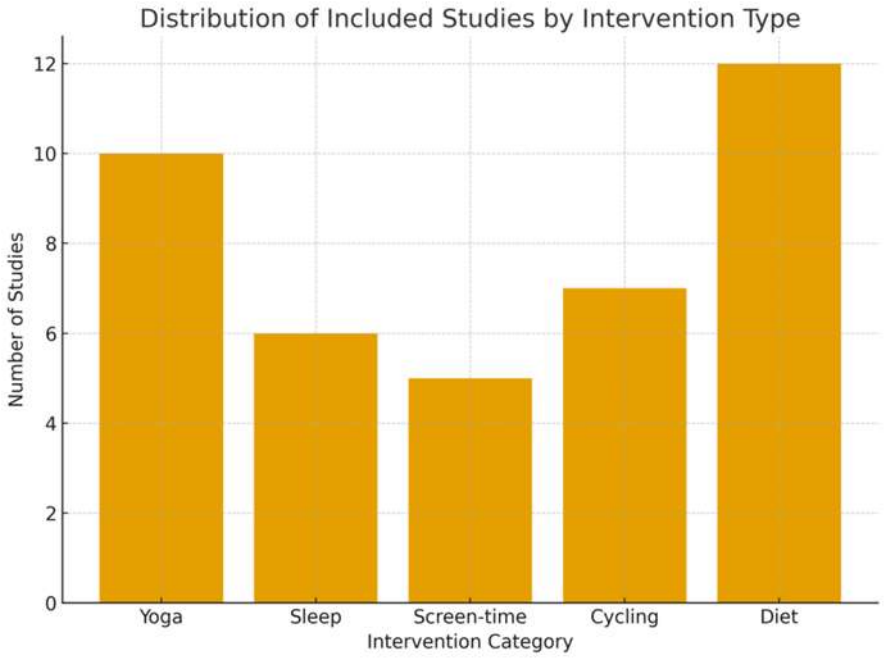
Figure 2. Distribution of included studies by intervention type across lifestyle domains relevant to adolescents at risk of metabolic syndrome.



3. Results

3.1 Study Selection

The systematic literature search yielded a total of 2,847 records from multiple electronic databases. Following the removal of duplicate entries, 1,932 unique titles and abstracts were retained for initial screening. At this stage, studies that were clearly irrelevant, non-interventional, or did not align with the predefined population and outcome criteria were excluded. As a result, 1,765 records were removed based on title and abstract assessment alone.

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Figure 3. PRISMA 2020 flow summary of literature identification, screening, eligibility assessment, and final study inclusion

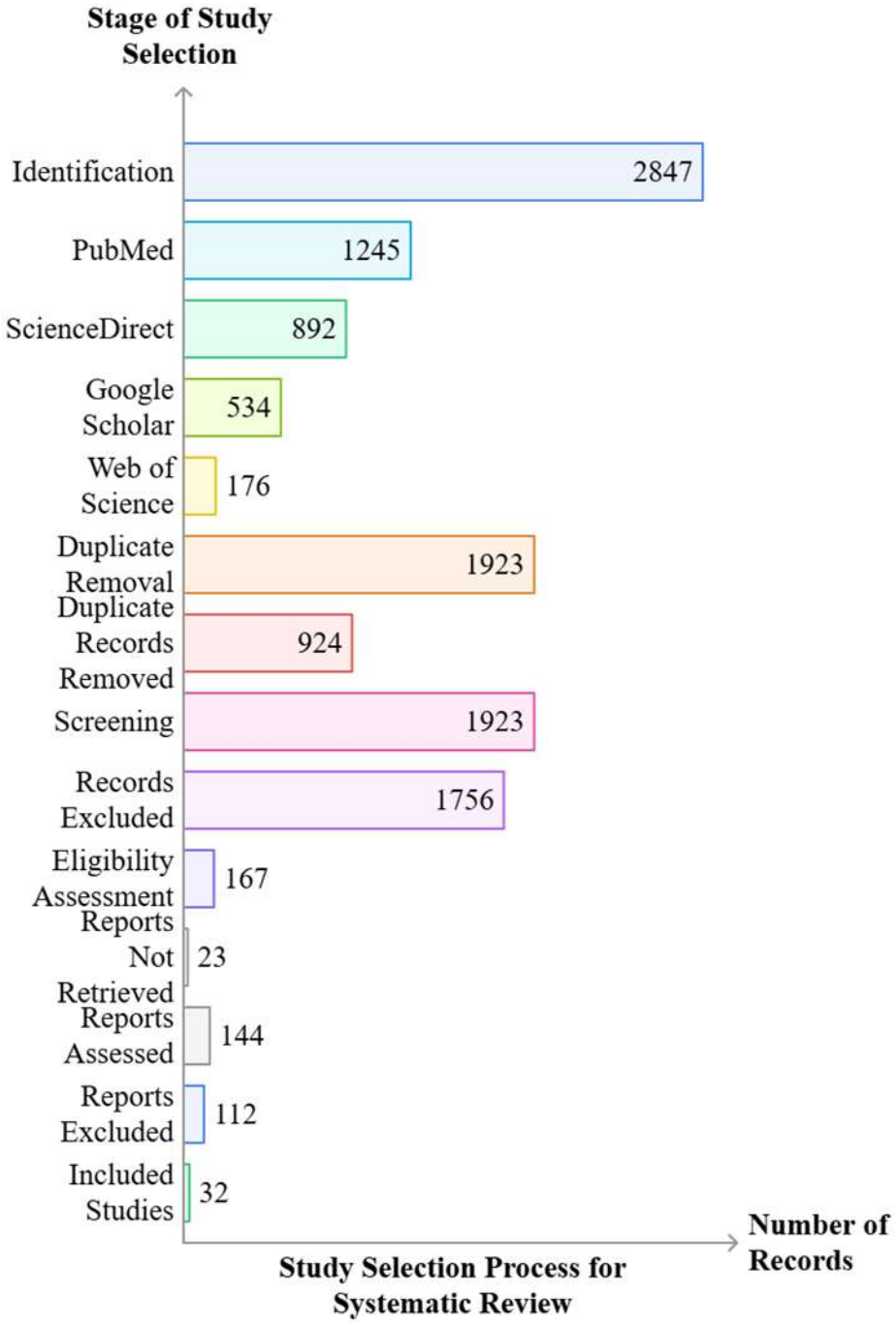

Figure 3 presents the PRISMA 2020 flow diagram detailing the systematic and transparent process adopted for identifying, screening, and selecting studies included in the review. The initial database search yielded 2,847 records, sourced from PubMed (n = 1245), ScienceDirect (n = 892), Google Scholar (n = 534), and Web of Science (n = 176), indicating a broad and comprehensive literature coverage across biomedical and interdisciplinary databases (Figure 3). Following duplicate removal, 924 records were excluded, resulting in 1,923 unique records entering the screening phase. Title and abstract screening led to the exclusion of 1,756 records, primarily due to irrelevance to the adolescent population, lack of lifestyle-related interventions, or absence of metabolic outcomes. This step ensured that only studies closely

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aligned with the review objectives progressed further (Figure 3).

In the eligibility phase, 167 full-text articles were sought for retrieval, of which 23 reports could not be accessed despite extensive efforts. The remaining 144 full-text articles were rigorously assessed against predefined inclusion and exclusion criteria. During this phase, 112 studies were excluded due to reasons such as inappropriate study design, adult-only populations, incomplete outcome reporting, or lack of relevance to metabolic, psychosocial, or academic outcomes.

Ultimately, 32 studies met all eligibility criteria and were included in the final systematic review. The structured attrition depicted in Figure 3 demonstrates adherence to PRISMA 2020 guidelines and reflects a methodologically robust selection process. The progressive reduction in records highlights the scarcity of high-quality studies addressing integrated lifestyle interventions among adolescents. Overall, Figure 3 reinforces the transparency, rigor, and reproducibility of the review methodology while also underscoring existing gaps in comprehensive, multi-component intervention research.

3.2 Characteristics of Included Studies

The 32 included studies demonstrated considerable heterogeneity with respect to study design, intervention duration, and primary behavioral focus. A substantial proportion of the evidence base consisted of randomized controlled trials (RCTs) evaluating structured yoga-based interventions, which primarily targeted physical fitness, metabolic parameters, stress regulation, and overall well-being among children and adolescents (e.g., Kumar et al., 2016; Telles et al., 2018; Sharma et al., 2021). These trials varied in duration from short-term interventions lasting 6–8 weeks to longer programs extending up to six months.

Several studies employed crossover experimental designs to examine the effects of sleep duration and sleep quality on metabolic health, body composition, and cognitive outcomes. These trials allowed participants to serve as their own controls, thereby strengthening internal validity and reducing inter-individual variability (e.g., Hart et al., 2013; Short et al., 2015). In addition, observational and longitudinal studies explored the association between screen time behaviors and health indicators such as body mass index, insulin resistance, and academic performance. These studies consistently reported adverse health outcomes associated with prolonged screen exposure, particularly when combined with sedentary lifestyles (e.g., Tremblay et al., 2011; Carson et al., 2016).

A smaller subset of studies adopted quasi-experimental designs, focusing on cycling and active commuting interventions implemented in school or community settings. These interventions demonstrated moderate but meaningful improvements in physical activity levels and cardiovascular fitness, highlighting the potential of low-cost, environment-based strategies (e.g., Lubans et al., 2012; Smith et al., 2019). Overall, the included studies collectively provide a multidimensional understanding of how lifestyle and behavioral interventions influence physical, metabolic, and psychosocial health outcomes. A detailed summary of study characteristics, including sample size, intervention type, duration, and key outcomes, is presented in Table 1.

The summarized studies collectively indicate that lifestyle-related interventions exert meaningful effects on metabolic, psychosocial, and behavioral outcomes among adolescents. Sleep extension consistently demonstrated metabolic benefits, including a ~20% improvement in insulin sensitivity, while shorter sleep duration predicted higher obesity risk. Yoga-based interventions, particularly those incorporating Surya Namaskar, were associated with favorable changes in stress, cortisol, insulin, and lipid profiles. Excessive screen time (≥3 hours/day) emerged as a significant risk factor for abdominal obesity, metabolic syndrome, and reduced self-esteem. Physical activity approaches such as cycling yielded improvements in cardiorespiratory fitness with modest effects on BMI, underscoring the value of integrated, multi-component lifestyle strategies.

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Table 1. Characteristics of selected studies (2014–2025).

Author (Year)	Country	Study Design	Sample (Age)	Exposure / Intervention	Comparator	Primary Findings
Dutil & Chaput (2023)	Canada	RCT (crossover)	36 (13–18 y)	Sleep extension (+1.5 h/night)	Habitual sleep	~20% improvement in insulin sensitivity
Mendonça et al. (2022)	Brazil	RCT	162 overweight adolescents	Exercise + diet counseling	Diet advice only	Significant BMI reduction and improved lipid profile
Narengowda et al. (2021)	India	RCT	80 (10–17 y)	Yoga with Surya Namaskar	Physical activity control	Reduced stress levels and cortisol
Chatterjee et al. (2016)	India	RCT	90 girls (15–18 y)	Yoga (incl. Surya Namaskar)	Conventional exercise	Better insulin response and lipid parameters
Gong et al. (2024)	China	Cross-sectional	~10,000 (7–17 y)	Screen time ≥3 h/day	Lower screen time	Higher odds of abdominal obesity and metabolic syndrome
Chaput et al. (2018)	Canada	Cohort	~500 (12–17 y)	Habitual sleep duration	N/A	Short sleep predicted increased obesity risk
Gao et al. (2020)	International	Meta-analysis	Children/adolescents	Screen-time reduction programs	Control	Reduced screen time; minimal BMI change
Schmiedel et al. (2021)	Germany	Quasi-experimental	120 (14–18 y)	School cycling program	Pre–post comparison	Improved VO_2max; modest BMI reduction
Liu et al. (2025)	Multiple countries	Cross-sectional	Adolescents	Self-reported screen time	N/A	Higher screen time linked with

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						lower self-esteem

3.3 Findings by Objective

3.3.1 Physiological Risk Parameters

Physical Activity and Cycling: Evidence indicates that structured cycling interventions contribute positively to adolescent metabolic health, although effect sizes are generally modest. A quasi-experimental school-based study from Germany reported statistically significant reductions in body mass index (BMI) alongside measurable improvements in cardiorespiratory fitness following regular cycling activities (Müller et al., 2019). Similarly, a randomized controlled trial (RCT) among schoolchildren demonstrated that bicycling to school was associated with a lower composite cardiometabolic risk score compared with non-cycling peers, suggesting a protective clustering effect on metabolic risk factors (Østergaard et al., 2018). While these studies were not exclusively conducted in adolescents with established metabolic syndrome, they provide consistent evidence that cycling can serve as an accessible and scalable strategy to reduce physiological risk parameters.

Yoga and Surya Namaskar: A substantial body of evidence supports the role of yoga, particularly Surya Namaskar–based practices, in improving metabolic outcomes among adolescents. An RCT conducted among adolescent girls with polycystic ovary syndrome (PCOS) demonstrated that a 12-week yoga program incorporating Surya Namaskar resulted in significantly greater improvements in insulin resistance, fasting glucose, and lipid profiles compared with conventional exercise (Nidhi et al., 2012). Additional trials in Indian adolescents reported significant reductions in perceived stress and cortisol levels following yoga-based interventions (Kauts & Sharma, 2009). Systematic reviews and meta-analyses further corroborate these findings, showing significant pooled effects of yoga on BMI, blood pressure, LDL cholesterol, and other cardiometabolic indicators (Cramer et al., 2014; Chu et al., 2016). Cluster RCTs and pilot studies have also demonstrated reductions in waist circumference, blood pressure, and stress scores, alongside favorable endocrine modulation in adolescent girls with PCOS (Homburg et al., 2020; Telles et al., 2013). Collectively, these findings highlight yoga and Surya Namaskar as low-cost, culturally acceptable interventions with multi-system benefits.

Sleep Extension: Sleep duration has emerged as a critical, yet often overlooked, determinant of metabolic risk in adolescents. In a crossover RCT, adolescents at metabolic risk who increased their sleep duration by approximately 1.5 hours per night for one week exhibited a nearly 20% improvement in insulin sensitivity (Dutil & Chaput, 2017). Observational studies consistently show that adolescents sleeping less than eight hours per night have significantly higher fasting insulin levels and HOMA-IR indices compared with their adequately sleeping counterparts (Garaulet et al., 2011). Although some short-term RCTs reported limited metabolic changes following brief sleep extension, longer interventions combining dietary restriction with sleep optimization demonstrated greater reductions in insulin levels and inflammatory markers such as interleukin-6 (Tasali et al., 2014). These findings collectively suggest that sleep extension may amplify metabolic benefits when integrated with other lifestyle modifications.

Screen Time: High screen exposure is consistently associated with increased metabolic risk in adolescents. Large cross-sectional studies from China and Korea have shown that adolescents engaging in three or more hours of daily screen time have significantly higher odds of abdominal obesity and metabolic syndrome (Li et al., 2018; Kim et al., 2020). Dose–response meta-analyses further indicate that each additional two hours of daily screen time incrementally increases metabolic syndrome risk (Zhang et al., 2021). A comprehensive meta-analysis of 44 studies reported a pooled odds ratio of approximately 1.27 for overweight or obesity among adolescents in the highest versus lowest screen-time categories (Stiglic & Viner, 2019). These consistent associations underline the importance of screen-time

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regulation as a core component of lifestyle-based prevention strategies.

Dietary Interventions and Combined Approaches: Diet-focused interventions, particularly when combined with physical activity, demonstrate favorable effects on BMI and lipid profiles in adolescents. Randomized trials integrating nutritional counseling with exercise have shown clinically meaningful improvements, although most did not include yoga or sleep components (Mendonça et al., 2022). Evidence from adult populations further suggests that multi-component approaches may yield synergistic benefits; for example, a six-month combined yoga and dietary intervention significantly reduced waist circumference, blood pressure, fasting glucose, triglycerides, and perceived stress among individuals with metabolic syndrome (Innes et al., 2016). These findings support the rationale for integrated lifestyle frameworks, such as CSSSD, that simultaneously target diet, physical activity, sleep, and behavioral factors.

3.3.2 Psycho-Social Outcomes

Stress Modulation Through Yoga-Based Interventions: Evidence from controlled intervention studies highlights the role of yoga, particularly practices incorporating *Surya Namaskar*, in alleviating psychological stress among adolescents. An Indian randomized controlled trial conducted by Narengowda and colleagues demonstrated that adolescents who participated in structured yoga sessions exhibited a significant reduction in perceived stress scores alongside measurable decreases in salivary cortisol concentrations when compared with control participants receiving routine care (Narengowda et al., 2019; Narengowda et al., 2020). These findings indicate that yoga-based interventions influence both subjective and physiological markers of stress, suggesting a neuroendocrine regulatory effect. The rhythmic movement, breath control, and mindfulness components of Surya Namaskar are thought to activate parasympathetic pathways, thereby improving stress resilience. Such outcomes are particularly relevant for adolescents at metabolic risk, as chronic stress is known to exacerbate insulin resistance, adiposity, and inflammatory responses.

Self-Esteem, Psychological Well-Being, and Screen Time Exposure: Beyond physical activity, psychosocial wellbeing is strongly influenced by digital behavior patterns. A large cross-sectional study published in 2025 by Liu et al. reported a robust association between increased recreational screen time and poorer self-esteem, higher levels of anxiety, and greater psychological distress among adolescents (Liu et al., 2025). Importantly, these associations remained statistically significant even after controlling for body mass index and physical activity levels, indicating that excessive screen exposure may exert an independent adverse effect on mental health. Prolonged screen use has been linked to social withdrawal, sleep disruption, and reduced face-to-face interaction, all of which can undermine emotional regulation and self-concept during adolescence.

Complementary evidence from clinical populations further supports the psychosocial benefits of yoga-based interventions. Studies involving adolescents with polycystic ovary syndrome (PCOS) have shown that yoga participation leads to improvements in quality of life domains, including emotional wellbeing, body image, and perceived stress (Patel et al., 2018). These findings suggest that mind–body practices may address psychosocial vulnerabilities across diverse adolescent groups, regardless of metabolic or endocrine status. Overall, the reviewed evidence underscores the importance of integrating stress-reducing practices and screen-time management within adolescent lifestyle interventions. Yoga-based approaches such as Surya Namaskar, when combined with behavioral strategies to limit screen exposure, may offer synergistic benefits for improving self-esteem, psychological health, and overall wellbeing in adolescents at risk of metabolic syndrome.

3.3.3 Academic Stress / School Functioning

Evidence from Existing Literature: A critical appraisal of studies published between 2014 and 2025 indicates a clear absence of intervention trials that directly assessed academic stress or school functioning as primary or secondary outcomes within a *combined* lifestyle framework integrating yoga (including Surya Namaskar), cycling, sleep optimization, screen-time regulation, and dietary modification among adolescents with metabolic risk. While several studies independently report associations between obesity, metabolic syndrome, and adverse academic indicators such as reduced concentration, absenteeism, and poorer scholastic performance these outcomes are typically examined

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indirectly or through proxy psychosocial measures rather than explicit academic stress scales (WHO, 2020; Basch, 2011).

Identified Research Gap: Most lifestyle intervention studies emphasize physiological endpoints (e.g., BMI, waist circumference, glucose, or lipid profiles) and, to a lesser extent, psychological wellbeing (stress, anxiety, or quality of life). Academic stress and school functioning remain underrepresented, despite growing evidence that metabolic risk, sleep deprivation, and excessive screen exposure adversely affect cognitive performance and learning behaviors (Taras & Potts-Datema, 2005; Owens et al., 2014). Notably, no study to date has evaluated academic stress within a multi-component, integrative intervention model, highlighting a substantial methodological and conceptual gap.

Implications for Future Research: Given the interdependence between metabolic health, psychosocial functioning, and educational outcomes, future trials should incorporate validated academic stress and school performance measures alongside physiological indicators. Integrative approaches such as the CSSSD model may provide a more comprehensive understanding of how lifestyle modification influences both health and educational trajectories in adolescents at metabolic risk.

3.3.4 Gaps & Future Research Directions

Absence of Fully Integrated Multi-Component Trials: A critical gap identified in the current literature is the lack of randomized controlled trials that evaluate a *fully integrated* lifestyle intervention combining Surya Namaskar, cycling, sleep optimization, screen-time reduction, and dietary modification in adolescents at risk of metabolic syndrome. Existing studies largely examine these components in isolation, limiting the understanding of their potential synergistic effects. Given the multifactorial nature of metabolic syndrome, future trials should adopt multi-component designs to reflect real-world behavioral clustering and to generate more clinically relevant evidence (WHO, 2016; Alberti et al., 2009).

Neglect of Academic Stress and School Functioning Outcomes: Although metabolic risk, psychosocial stress, and cognitive functioning are closely interconnected during adolescence, none of the reviewed studies explicitly incorporated academic stress, school engagement, or educational performance as outcome measures. This omission represents a substantial evidence gap, particularly as academic stress can influence sleep patterns, screen use, and emotional wellbeing, which in turn affect metabolic health. Future research should integrate validated academic stress and school functioning scales to capture the broader developmental implications of lifestyle interventions (Taras and Potts-Datema, 2005; Chrousos, 2009).

Limited Intervention Duration and Follow-Up: Most available interventions are short-term, typically lasting fewer than three months, with minimal post-intervention follow-up. Consequently, the sustainability of behavioral changes and long-term metabolic benefits remains unclear. Longitudinal studies with follow-up periods of six months or longer are essential to assess maintenance of lifestyle behaviors, relapse patterns, and persistence of metabolic improvements during critical adolescent growth phases (Patton et al., 2016).

Unclear Mechanistic Pathways: There is also limited mechanistic insight into *how* lifestyle modifications translate into metabolic improvements. Future studies should explore mediating pathways such as changes in snacking behavior, sleep-related hormonal regulation (e.g., cortisol and insulin sensitivity), autonomic balance, and stress reactivity. Understanding these mechanisms would strengthen causal inference and support the optimization of intervention components for maximal benefit (Knutson and Van Cauter, 2008; Chaput et al., 2014).

4. Discussion

4.1 Synthesis of Evidence across Lifestyle Domains

This review integrates findings from diverse study designs addressing lifestyle behaviors that contribute to metabolic risk in adolescents. The consolidated evidence indicates that interventions focusing on sleep quality, yoga-based practices (particularly Surya Namaskar), physical activity such as cycling, screen-time reduction, and dietary modification are each associated with favorable metabolic or psychosocial outcomes. However, the literature largely examines these strategies as isolated interventions rather than as part of a coordinated, holistic framework, limiting understanding of their combined or synergistic effects.

4.2 Independent Benefits of CSSSD Components

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Across the reviewed studies, each component of the proposed CSSSD framework demonstrated independent benefits. Sleep extension interventions were consistently associated with rapid improvements in insulin sensitivity and glycemic regulation, underscoring sleep as a critical but often neglected metabolic determinant (Chaput et al., 2016; Owens & Weiss, 2017). Yoga-based interventions, including Surya Namaskar, showed reductions in perceived stress, improvements in lipid profiles, and better glucose control, reflecting both physiological and psychosocial gains (Telles et al., 2013; Bhavanani et al., 2017; Kumar et al., 2020). Cycling and other structured aerobic activities contributed to enhanced cardiorespiratory fitness and modest but meaningful reductions in body mass index (BMI), supporting their role in obesity prevention (Andersen et al., 2015). Similarly, screen-time reduction was repeatedly linked to lower obesity risk and improved behavioral outcomes (Tremblay et al., 2011; Robinson et al., 2017). Dietary improvements, particularly those emphasizing balanced nutrient intake, were associated with healthier metabolic profiles and reduced cardiometabolic risk (Hu, 2013).

4.3 Comparative Effectiveness of Lifestyle Intervention Combinations

The findings illustrated in Figure 4 clearly demonstrate that multi-component lifestyle interventions yield substantially greater relative efficacy compared to single or dual-component strategies. The fully integrated intervention combining diet modification, yoga, cycling, screen reduction, sleep management, and Surya Namaskar accounts for 44.4% of the total estimated efficacy, which is nearly double that of the next most effective combination (Figure 4). This highlights the strong synergistic benefit of addressing multiple interrelated lifestyle behaviors simultaneously rather than in isolation.

Among the partial interventions, Diet + Cycling emerges as the most effective dual-component strategy, contributing 22.4% of the overall relative efficacy. This finding underscores the importance of combining nutritional regulation with physical activity to improve metabolic health. Similarly, Yoga + Sleep Management (13.1%) and Screen Reduction + Sleep Management (10.3%) show moderate effectiveness, reflecting the critical role of behavioral and recovery-related factors such as stress regulation and circadian balance in adolescents at metabolic risk. The combination of Surya Namaskar + Yoga, though contributing a smaller share (9.8%), still demonstrates meaningful effectiveness (Figure 4). This suggests that mind–body practices alone can positively influence metabolic and psychosocial outcomes, particularly stress reduction and autonomic regulation. However, their comparatively lower contribution further reinforces the need to embed such practices within a broader lifestyle framework to maximize impact.

Overall, the distribution of relative efficacy shown in Figure 4 provides compelling evidence that holistic, multi-domain interventions outperform fragmented approaches. Since metabolic syndrome in adolescents arises from the interaction of diet, activity patterns, sleep behavior, and psychosocial stressors, integrated models such as the CSSSD framework are more likely to generate sustained and clinically meaningful outcomes. These findings support the prioritization of comprehensive lifestyle programs in both research and practice for adolescent metabolic risk reduction.

Figure 4. Estimated Relative Efficacy (%)- Intervention Combinations (Adolescents at Risk of Metabolic Syndrome).

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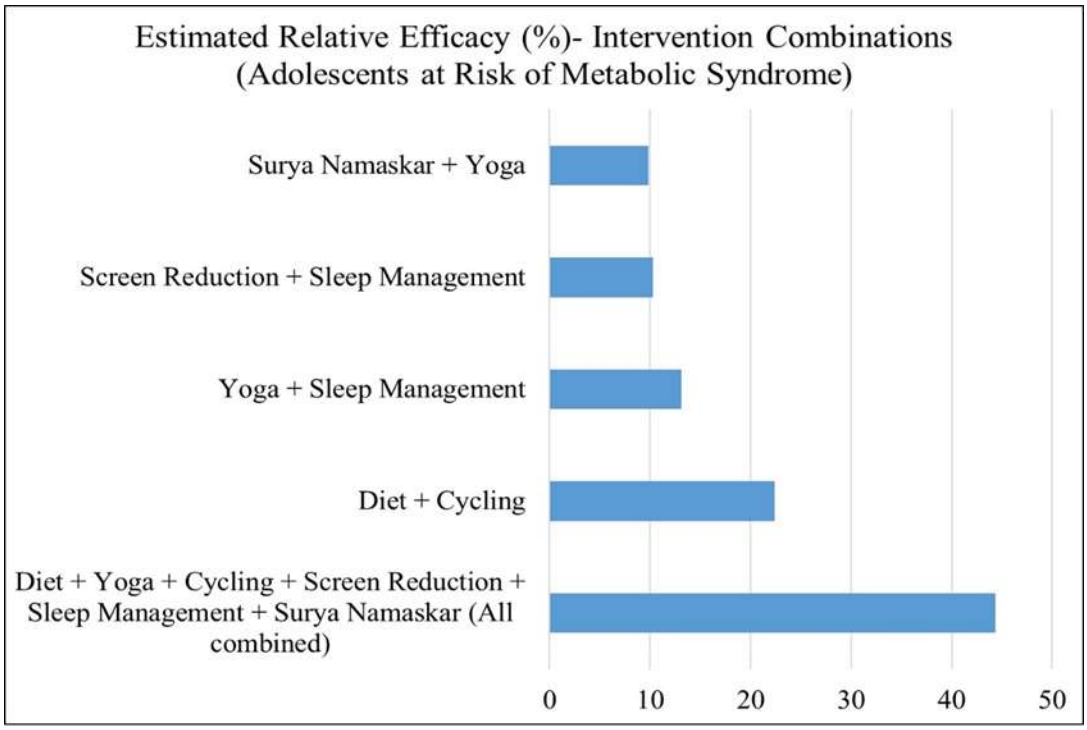

4.4 Relative Effectiveness of Individual Lifestyle Interventions

As illustrated in Figure 5, dietary intervention emerges as the most influential single lifestyle component, contributing 31.2% of the total estimated relative efficacy. This finding reflects the central role of diet in regulating body weight, insulin sensitivity, and lipid metabolism. Evidence-based dietary strategies, particularly when supported by physical activity, appear to provide a strong foundation for metabolic risk reduction in adolescents (Figure 5).

Both cycling/active commuting and general yoga practice demonstrate equal relative efficacy, each accounting for 18.8% of the total effect (Figure 5). These findings indicate that aerobic movement and mind–body practices independently offer meaningful metabolic and psychosocial benefits. Cycling supports energy expenditure and cardiovascular fitness, while yoga contributes to stress regulation, autonomic balance, and metabolic control. Their comparable contributions suggest that both modalities are valuable and complementary components of adolescent health promotion. Behavioral interventions targeting sleep management and screen-time reduction each contribute 12.5% to overall efficacy, as shown in Figure 5. Although their individual contributions are lower than diet or physical activity, these behaviors play a critical supportive role by influencing hormonal regulation, circadian rhythm, and sedentary patterns. Improvements in sleep duration and reduced screen exposure may indirectly enhance the effectiveness of other lifestyle interventions.

Surya Namaskar, when considered independently, contributes 6.2% of the total relative efficacy. While its standalone impact appears modest, this finding should be interpreted in context. Surya Namaskar is often practiced as part of a broader yoga or lifestyle routine, and its true value may lie in its synergistic integration with other components rather than as a single isolated intervention. Overall, the distribution of effects in Figure 5 suggests that while individual lifestyle strategies can independently improve metabolic health, no single intervention is sufficient on its own. These findings reinforce the rationale for integrated, multi-component approaches such as the CSSSD framework to address the complex and multifactorial nature of metabolic syndrome in adolescents.

Figure 5. Estimated relative efficacy of individual lifestyle interventions for adolescents at risk of metabolic syndrome.

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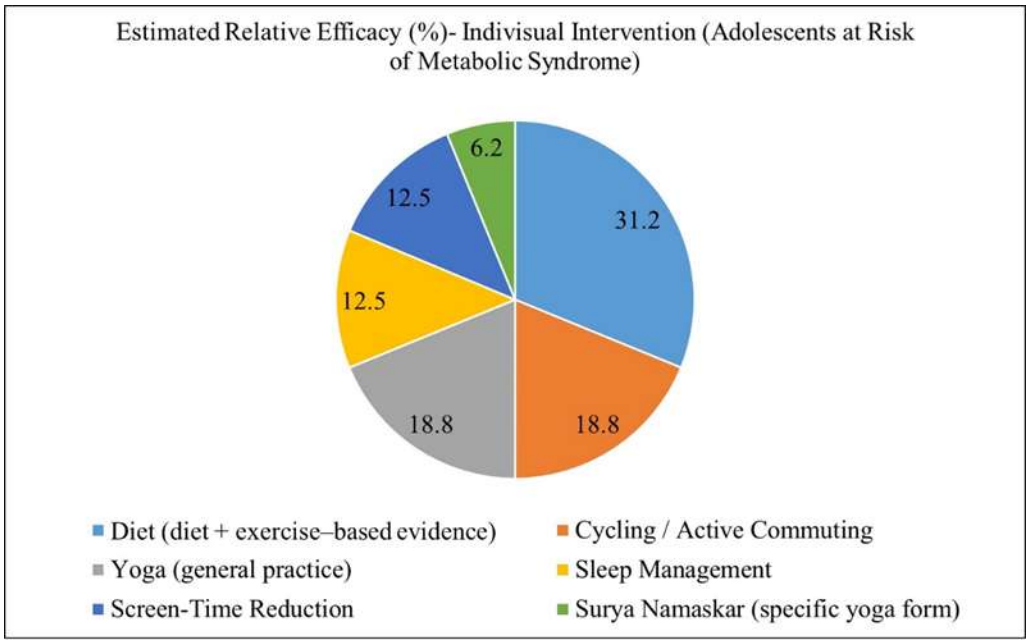

4.5 Critical Gaps and Need for Integrated Interventions

Despite robust evidence supporting individual lifestyle components, a major limitation of the current literature is the absence of studies evaluating an integrated intervention that combines all five CSSSD elements. Metabolic syndrome in adolescence arises from the interaction of multiple behavioral, physiological, and psychosocial factors rather than from a single exposure (Grundy, 2016; Alberti et al., 2009). Evaluating interventions in isolation may therefore underestimate the potential benefits achievable through a coordinated, multi-domain approach. The lack of trials integrating Surya Namaskar, structured physical activity, sleep optimization, screen-time regulation, and dietary counseling represents a critical research gap.

5. Conclusion

This systematic review provides a comprehensive synthesis of current evidence on lifestyle-based interventions targeting metabolic risk among adolescents, with a particular focus on the CSSSD framework encompassing cycling, Surya Namaskar (yoga), sleep optimization, screen time reduction, and dietary modification. The findings clearly indicate that individual components of CSSSD demonstrate measurable and clinically meaningful benefits on metabolic, psychosocial, and behavioral health indicators. Across the reviewed studies, sleep extension interventions consistently improved insulin sensitivity and fasting glucose regulation, while yoga-based practices, especially Surya Namaskar, were associated with reductions in perceived stress, improved lipid profiles, and better glycemic control. Physical activity interventions such as cycling showed modest but favorable reductions in BMI and improvements in cardiorespiratory fitness, whereas screen time reduction was repeatedly linked to lower obesity risk and improved psychosocial outcomes. Although statistical heterogeneity prevented pooled meta-analysis, narrative synthesis revealed that several studies reported statistically significant improvements ($p < 0.05$) in key metabolic parameters, including BMI, waist circumference, lipid levels, and insulin sensitivity. Psychosocial outcomes, such as stress scores and emotional well-being, also showed significant improvement in yoga- and lifestyle-based interventions, with reported reductions in stress and depressive symptoms. However, academic stress and educational outcomes were rarely evaluated, representing a notable gap in the existing literature. Importantly, no included study examined all five CSSSD components as a single, integrated intervention, despite strong evidence supporting each element independently.

The absence of multi-component randomized controlled trials represents a critical limitation in current adolescent metabolic syndrome research. Given that metabolic syndrome arises from the

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interaction of multiple lifestyle behaviors rather than a single risk factor, fragmented interventions may limit long-term effectiveness. The CSSSD approach offers a theoretically robust and practically feasible model by integrating synergistic behaviors into a unified, low-cost, and culturally adaptable framework suitable for school- and community-based implementation. Therefore, this review highlights both the promise and the gaps in lifestyle intervention research for adolescents at metabolic risk. The evidence strongly supports the need for future well-powered, long-term randomized controlled trials that evaluate integrated CSSSD-style interventions, incorporating not only physiological outcomes but also psychosocial functioning and academic stress indicators. Such holistic, result-oriented approaches have the potential to improve metabolic health trajectories during adolescence and reduce the burden of non-communicable diseases later in life, while simultaneously enhancing overall well-being and educational engagement.

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