

Effects of a 12-Week Bodyweight Circuit Training Program Combined with Green Tea Consumption on Insulin Resistance and Body Composition in Sedentary Overweight Adolescent Boys

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Article Info	Abstract
Article type: Research Article Article history: Received 02 February 2026 Received in revised form 05 April 2026 Accepted 22 April 2026 Available online 29 June 2026 Keywords: Insulin Resistance, Adolescent, Overweight, Exercise, Tea.	Introduction: Insulin resistance (IR) during adolescence is closely associated with excess adiposity and low physical activity and increases future cardiometabolic risk. School-based exercise programs are scalable; however, evidence on whether green tea intake enhances exercise-related metabolic benefits in overweight adolescents is limited. Objective: To investigate the effects of a 12-week bodyweight circuit training program, alone or combined with daily green tea consumption, on IR and body composition (BC) in sedentary overweight adolescent boys. Method: In this three-arm randomized controlled trial, sedentary overweight boys (14–17 years; BMI-for-age 85th–94th percentile) were randomized to Exercise + Green Tea (EX+GT), Exercise only (EX), or Control (CON). Exercise groups completed a school-based bodyweight circuit program twice weekly (60 min/session) for 12 weeks. The EX+GT group consumed 2 cups/day of green tea. Fasting glucose and insulin were measured to calculate HOMA-IR. Secondary outcomes included body mass, BMI, waist circumference, waist-to-height ratio (WHtR), body fat percentage, and fat-free mass. Outcomes were assessed at baseline and post-intervention and analyzed using ANCOVA. Results: A significant group effect was observed for HOMA-IR ($p < 0.001$). HOMA-IR decreased in EX+GT (4.31 ± 0.93 to 3.12 ± 0.71) and EX (4.19 ± 0.88 to 3.54 ± 0.76), with minimal change in CON. EX+GT improved HOMA-IR more than EX ($p = 0.041$). Significant group effects were also found for body mass, BMI, waist circumference, WHtR, and body fat percentage (all $p < 0.05$), generally favoring EX+GT. Conclusions: A brief twice-weekly school-based bodyweight circuit program improved IR and BC in overweight adolescent boys, with greater metabolic benefit when combined with daily green tea consumption. Cite this Article: Teimoori, A. (2026). Effects of a 12-Week Bodyweight Circuit Training Program Combined with Green Tea Consumption on Insulin Resistance and Body Composition in Sedentary Overweight Adolescent Boys. <i>Physical Activity in Children</i>, 3(1), 73-81. https://doi.org/10.22034/pach.2026.587108.1094

1. Introduction

Overweight during adolescence is a major public health concern because excess adiposity that develops early in life often persists into adulthood and is associated with elevated cardiometabolic risk (1). Beyond changes in body weight alone, one of the most clinically relevant metabolic disturbances in overweight youth is insulin resistance (IR), a condition in which peripheral tissue exhibit a reduced response to insulin (2). In adolescents, IR can emerge even in the absence of overt hyperglycemia and may precede dysglycemia, metabolic syndrome, and type 2 diabetes (3). Importantly, IR in youth is also linked to early vascular dysfunction, unfavorable inflammatory profiles, and clustering of risk factors that increase lifetime disease burden (4,5). Therefore, identifying feasible strategies that improve insulin sensitivity during adolescence is a priority for prevention-focused pediatric exercise and health research.

Physical activity (PA) is widely recognized as a cornerstone intervention for improving metabolic

health (6,7). Exercise enhances insulin sensitivity acutely through insulin-independent glucose uptake pathways and chronically through adaptations including improved mitochondrial function, greater skeletal muscle oxidative capacity, increased GLUT4 expression, enhanced capillary density, and reductions in systemic inflammation (8,9). However, many adolescents, especially those with overweight, do not meet recommended PA guidelines, and participation in organized sport or fitness programs is often limited by cost, access, motivation, and time constraints (10-12). These barriers have driven interest in school-based interventions, which offer a practical environment for structured exercise programs with broad reach, consistent scheduling, lower logistical burden, and relatively low implementation costs. Because schools provide access to large numbers of adolescents regardless of socioeconomic status, they represent an important setting for scalable public health strategies targeting physical inactivity and metabolic health (10-12).



Within the spectrum of exercise modalities, circuit-style training is especially attractive for school settings. Bodyweight circuit training can be implemented without specialized equipment and can be scaled by modifying movement complexity, work-to-rest ratios, and the number of rounds performed (13,14). Circuit formats can simultaneously target muscular endurance, strength, and cardiorespiratory demand, potentially producing meaningful changes in body composition (BC) and metabolic function (15-17). For overweight adolescents, circuit training may be particularly suitable because it allows progressive increases in training load while maintaining variety and engagement (10,18). Despite this promise, the optimal approach for maximizing improvements in IR with a minimal weekly time commitment remains an important research question.

In parallel with exercise-based strategies, there is substantial interest in adjunct nutritional approaches that may enhance metabolic outcomes (19). Green tea is one of the most commonly consumed beverages worldwide and contains bioactive compounds including catechins, most notably epigallocatechin gallate (EGCG), as well as caffeine in modest amounts (20). Mechanistically, green tea catechins have been suggested to influence glucose metabolism through antioxidant and anti-inflammatory actions, modulation of insulin signaling pathways, and potential effects on lipid oxidation and energy expenditure (21). Experimental evidence also suggests that EGCG may activate AMP-activated protein kinase (AMPK), thereby promoting glucose uptake and fatty-acid oxidation; however, evidence in humans remains inconsistent and appears to depend on dose, intervention duration, and participant characteristics. Some studies in adults and clinical populations suggest that green tea or catechin-rich extracts may modestly improve markers of metabolic health, including fasting insulin and indices of IR (22-25), although findings are inconsistent and may depend on dose, duration, baseline metabolic status, and adherence. Evidence in adolescent populations remains comparatively limited, and interventions that combine green tea intake with structured exercise are underexplored.

The rationale for combining exercise training with green tea consumption is based on the possibility of additive physiological effects. Exercise provides a potent physiological stimulus for improving glucose transport and insulin signaling in skeletal muscle (26), while green tea catechins may support a metabolic milieu that favors improved insulin action by reducing oxidative stress and inflammation, factors known to impair insulin sensitivity (27). Additionally, small effects of green tea on energy balance or fat oxidation could complement exercise-induced changes in BC, particularly reductions in central adiposity, which are strongly associated with IR in youth (28,29). Although these mechanisms are biologically plausible, relatively few randomized studies have examined whether combining bodyweight exercise with green tea produces greater metabolic benefits than exercise alone in overweight adolescents.

Another key consideration is the importance of examining outcomes beyond BMI. In adolescents, BMI is useful for population screening but does not distinguish between fat mass and lean mass and may

not fully capture changes in central adiposity (30). Measures such as waist circumference and waist-to-height ratio (WHtR) are particularly relevant for cardiometabolic risk, as abdominal adiposity is closely tied to IR and adverse lipid and inflammatory profiles (31). Similarly, estimating body fat percentage and fat-free mass can help clarify whether improvements in metabolic health are mediated by reductions in adiposity, changes in lean tissue, or both. Therefore, a comprehensive assessment of BC alongside IR provides a more informative evaluation of intervention effects.

Despite increasing interest in exercise-based interventions for adolescent obesity, few randomized controlled trials have simultaneously examined IR and multiple body-composition outcomes following a low-cost school-based bodyweight circuit training program, and even fewer have evaluated whether adding a practical nutritional strategy such as daily green tea consumption provides additional benefit. Given these gaps, the present study investigated the effects of a 12-week school-based bodyweight circuit training program, performed alone or combined with daily green tea consumption on IR and BC in sedentary overweight adolescent boys. It was hypothesized that: (1) both exercise interventions would significantly improve HOMA-IR and BC compared with the control group, and (2) participants receiving bodyweight circuit training combined with daily green tea consumption would demonstrate greater improvements in IR and central adiposity-related outcomes than those performing exercise alone.

2. Methods

2.1. Study Design

This study was conducted as a three-arm, parallel-group randomized controlled trial.

2.2. Participants

Participants were adolescent boys aged 14-17 years recruited from local schools. Overweight status was defined using age- and sex-specific growth references as BMI-for-age between the 85th and 94th percentiles. Sedentary status was defined as not participating in any structured exercise program during the previous 3 months and not meeting recommended levels of PA based on screening questionnaire. Participants were eligible for inclusion if they were male adolescents aged 14-17 years, classified as overweight according to BMI-for-age percentiles (85th-94th percentile), sedentary at baseline, and free from diagnosed metabolic, cardiovascular, or endocrine disorders. All participants provided written assent, and written informed consent was obtained from their parents or legal guardians. Participants were excluded if they had type 1 or type 2 diabetes, were using medications known to affect glucose metabolism, or had musculoskeletal limitations that would preclude safe participation in exercise training. Additional exclusion criteria included the use of weight-loss supplements, habitual consumption of green tea or concentrated tea products prior to enrollment, caffeine sensitivity or other contraindications to tea consumption, and initiation of any new diet or exercise program during the study period.

An a priori sample size calculation was performed using G*Power (version 3.1.9.6). Assuming a large effect

size ($f = 0.40$) for changes in HOMA-IR based on previous exercise intervention studies in overweight adolescents (10,18), an alpha level of 0.05, statistical power of 80%, and three parallel groups with repeated measurements, a minimum sample size of 45 participants was required. To account for an anticipated attrition rate of approximately 15%, the target recruitment sample was increased to 58 participants.

After baseline testing, participants were randomized to EX+GT, EX, or CON using a computer-generated random sequence. Allocation concealment was ensured using sequentially numbered, opaque, sealed envelopes prepared by an investigator not involved in recruitment or outcome assessment. Due to the behavioral nature of the intervention, participants and trainers could not be blinded to exercise assignment. Outcome assessors and laboratory personnel were blinded to group allocation when feasible. Because green tea was provided as a beverage without a placebo, blinding for the supplementation component was not implemented.

2.3. Interventions

2.3.1. Bodyweight Circuit Training

Participants allocated to the EX+GT and EX groups completed a 12-week, school-based, supervised bodyweight circuit training program performed twice weekly on non-consecutive days. Each session lasted approximately 60 minutes and was delivered by trained exercise staff. All exercise sessions were supervised by the same certified exercise physiologist following a standardized intervention protocol to ensure consistency across sessions. Each session consisted of: (1) a 10-min warm-up including light jogging, mobility drills, and dynamic stretching; (2) 40–45 min of circuit-based bodyweight training targeting major muscle groups; and (3) a 5–10 min cool-down comprising low-intensity movements and static stretching. A typical circuit included 8–10 stations (e.g., squats, lunges, push-ups, plank variations, mountain climbers, burpees, step-ups, jumping jacks, and sit-ups). Participants completed the circuit in rounds. Progression was implemented every 2–3 weeks by increasing the number of rounds and/or the duration of work intervals, and by advancing exercise complexity while maintaining correct technique and safe movement patterns. Rest intervals were standardized between stations and between rounds. Training intensity was prescribed to elicit a moderate-to-vigorous effort corresponding to approximately 65–85% of age-predicted maximal heart rate and a rating of perceived exertion (RPE) of 13–16 on the Borg 6–20 scale. Exercise intensity was monitored by trained instructors using the Borg RPE scale throughout each session. Attendance was recorded at each session, and adverse events were monitored throughout the intervention.

2.3.2. Green Tea Consumption

Participants in the EX+GT group were instructed to consume two cups of green tea per day for 12 weeks. The green tea was supplied as commercially available tea bags. Each tea bag contained approximately 2 g of dried green tea leaves, providing approximately 280–320 mg total catechins, including approximately 140–160 mg EGCG, and approximately 30–35 mg caffeine per serving. Participants consumed two servings daily

(total daily intake: approximately 560–640 mg catechins, 280–320 mg EGCG, and 60–70 mg caffeine). Tea was prepared using 250 mL of hot water (approximately 80–85°C) with a standardized brewing time of 3 minutes. One cup was consumed in the morning and the second in the afternoon/evening, with guidance to avoid intake close to bedtime. Participants were asked to maintain their habitual diet and to avoid initiating other tea-based products or supplements during the study.

2.3.3. Control Group

Participants in the CON group were instructed to continue their usual activities and not to initiate structured exercise training or dietary supplementation during the 12-week period. They received general health information consistent with routine school guidance.

2.4. Measurements

All measurements were assessed at baseline and post-intervention under standardized conditions.

2.4.1. Insulin Resistance

After a 10–12 hour overnight fast, venous blood samples were collected in the morning. Fasting plasma glucose was analyzed using an automated enzymatic method, whereas fasting serum insulin was determined using ELISA. The intra-assay and inter-assay coefficients of variation for insulin measurements were <4.5% and <6.2%, respectively. IR was calculated using the homeostatic model assessment of IR (HOMA-IR):

$$\text{HOMA-IR} = \frac{\text{Fasting insulin}(\mu\text{U/mL}) \times \text{Fasting glucose}(\text{mg/dL})}{405}$$

2.4.2. Body Composition and Anthropometry

Body mass (kg) and height (cm) were measured using calibrated equipment, and BMI (kg/m^2) was calculated. Waist circumference was measured using a non-elastic tape at a standardized anatomical site, and WHtR was computed. Body fat percentage and fat-free mass were assessed using a multifrequency bioelectrical impedance analyzer (e.g., InBody 270, Biospace Co., Seoul, South Korea). Measurements were performed in the morning after an overnight fast, following bladder emptying and before vigorous PA, according to the manufacturer's recommendations. Calibration procedures were conducted before each testing session.

2.5. Additional Monitoring

Participants were asked to maintain their usual dietary intake throughout the study. To minimize dietary confounding, participants completed 3-day food records (two weekdays and one weekend day) at baseline and during the final intervention week. Dietary records were reviewed by a registered nutritionist to verify that no major dietary changes occurred during the intervention. Habitual PA outside the supervised sessions was monitored using the Physical Activity Questionnaire for Adolescents (PAQ-A), administered at baseline and post-intervention. Participants were also instructed not to initiate any additional structured exercise during the study period. Compliance with green tea intake was monitored using a simple daily log and weekly checks by the research team. Mean compliance with green tea consumption was $94.2 \pm 4.8\%$. Exercise adherence was

quantified by attendance. Mean attendance at supervised exercise sessions was $91.3 \pm 5.2\%$.

2.6. Statistical Analysis

Data were analyzed using IBM SPSS Statistics (Version 27.0; IBM Corp., Armonk, NY, USA) with significance set at $p < 0.05$. Normality was examined using the Shapiro-Wilk test. Baseline differences were examined using one-way ANOVA (continuous variables) and chi-square tests (categorical variables). Primary and secondary outcomes were analyzed using ANCOVA, with baseline values as covariates. Where overall group effects were significant, Bonferroni-adjusted pairwise comparisons were performed. Adjusted mean differences with 95% confidence intervals (95% CI) were calculated for all primary outcomes. Effect sizes were reported as partial eta-squared (η^2).

3. Results

3.1. Participant Flow and Adherence

A total of 58 adolescents were screened for eligibility. Of these, 45 met the inclusion criteria and were randomly assigned to one of three groups: EX+GT ($n=15$), EX ($n=15$), or CON ($n=15$). During the intervention, 3 participants withdrew: 1 from EX+GT due to irregular school attendance, 1 from EX due to lack of interest, and 1 from CON because of relocation. Thus, 42 participants completed the study and were included in the final analysis: EX+GT ($n=14$), EX ($n=14$), and CON ($n=14$) (Figure 1). Mean exercise attendance was 89.3% in EX+GT and 87.5% in EX. Compliance with green tea consumption in the EX+GT group, based on daily logs and weekly monitoring, was estimated at 91.0%. No serious adverse events were reported (Figure 1).

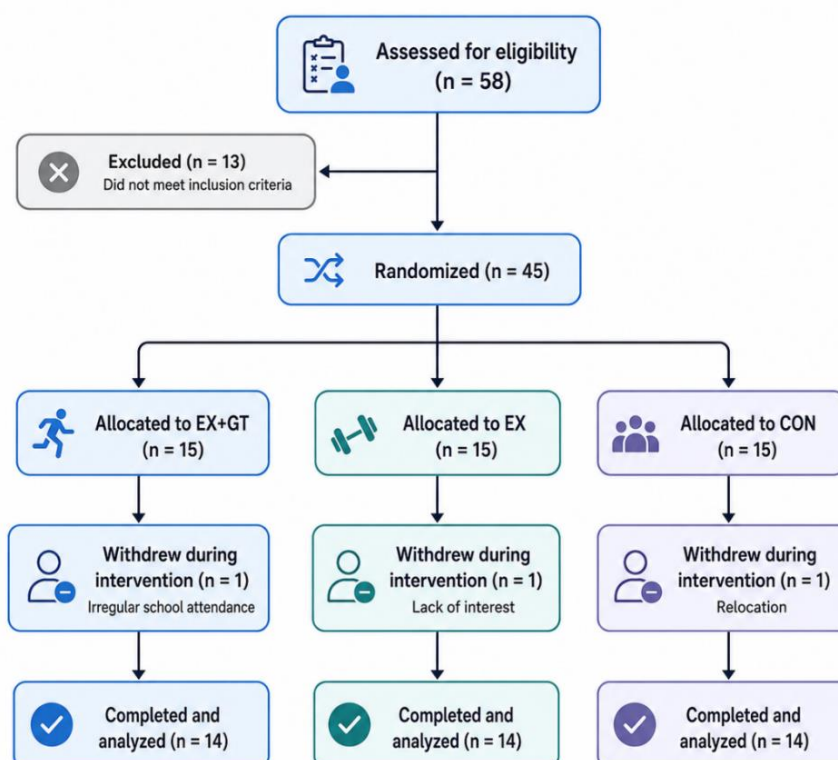


Figure 1. The CONSORT Flow Chart

3.2. Baseline Characteristics

Baseline demographic, anthropometric, and metabolic characteristics were comparable among

groups, with no significant between-group differences at study entry ($p > 0.05$ for all) (Table 1).

Table 1. Baseline Characteristics of Participants.

Variable	EX+GT	EX	CON	p
Age (years)	15.6 $\pm$ 1.0	15.4 $\pm$ 1.1	15.5 $\pm$ 0.9	0.84
Height (cm)	168.7 $\pm$ 6.1	167.9 $\pm$ 5.8	169.2 $\pm$ 6.4	0.79
Body Mass (kg)	73.8 $\pm$ 6.9	72.6 $\pm$ 7.4	74.1 $\pm$ 7.1	0.88
BMI (kg/m ²)	25.9 $\pm$ 1.4	25.7 $\pm$ 1.5	26.0 $\pm$ 1.6	0.91
Waist Circumference (cm)	88.4 $\pm$ 4.8	87.9 $\pm$ 5.1	88.8 $\pm$ 4.6	0.87
WHR	0.52 $\pm$ 0.02	0.52 $\pm$ 0.03	0.53 $\pm$ 0.03	0.76
Body fat (%)	29.8 $\pm$ 3.1	29.4 $\pm$ 3.4	30.1 $\pm$ 3.0	0.83
Fat-free Mass (kg)	51.8 $\pm$ 4.0	51.3 $\pm$ 4.2	51.5 $\pm$ 4.1	0.94
Fasting Glucose (mg/dL)	94.2 $\pm$ 5.8	93.7 $\pm$ 5.4	94.8 $\pm$ 5.9	0.89
Fasting Insulin (μ U/mL)	18.5 $\pm$ 3.7	18.1 $\pm$ 3.5	18.8 $\pm$ 3.9	0.92
HOMA-IR	4.31 $\pm$ 0.93	4.19 $\pm$ 0.88	4.40 $\pm$ 0.95	0.86

3.3. Primary Outcome: HOMA-IR

Significant between-group differences were observed in glucose metabolism outcomes. After adjustment for baseline values, ANCOVA showed a significant overall group effect for the primary outcome, HOMA-IR ($F_{2,38}=22.58$, $p<0.001$, $\eta^2=0.45$). Significant between-group differences were also observed for fasting insulin ($F_{2,38}=19.47$, $p<0.001$, $\eta^2=0.33$), whereas the between-group difference for fasting glucose was smaller and did not reach statistical significance ($F_{2,38}=2.52$, $p=0.091$, $\eta^2=0.12$) (Table 2 and Figure 2).

The adjusted mean reduction in HOMA-IR was -1.17 (95% CI: -1.52 to -0.82) in the EX+GT group and -0.63 (95% CI: -0.95 to -0.31) in the EX-group relative to baseline, whereas the control group showed no meaningful change (-0.05 ; 95% CI: -0.29 to 0.19). Furthermore, the mean post-intervention HOMA-IR value in the EX+GT group approached values generally considered indicative of improved insulin sensitivity in adolescents, whereas the control group remained within the insulin-resistant range.

Table 2. Changes in glucose metabolism outcomes.

Variable	EX+GT	EX	CON	p	Partial η^2	95% CI (Adjusted Mean Difference vs CON)
Fasting Glucose (mg/dL)	94.2 $\pm$ 5.8 $\rightarrow$ 91.1 $\pm$ 5.0	93.7 $\pm$ 5.4 $\rightarrow$ 92.0 $\pm$ 5.1	94.8 $\pm$ 5.9 $\rightarrow$ 94.5 $\pm$ 5.7	0.091	0.12	-2.1 to 0.4
Fasting Insulin (μ U/mL)	18.5 $\pm$ 3.7 $\rightarrow$ 13.9 $\pm$ 2.9	18.1 $\pm$ 3.5 $\rightarrow$ 15.4 $\pm$ 3.1	18.8 $\pm$ 3.9 $\rightarrow$ 18.5 $\pm$ 3.6	<0.001	0.33	-5.6 to -2.1
HOMA-IR	4.31 $\pm$ 0.93 $\rightarrow$ 3.12 $\pm$ 0.71	4.19 $\pm$ 0.88 $\rightarrow$ 3.54 $\pm$ 0.76	4.40 $\pm$ 0.95 $\rightarrow$ 4.34 $\pm$ 0.91	<0.001	0.45	-1.52 to -0.82

3.4. Secondary Outcomes: Body Composition and Anthropometry

Significant overall group effects were found for body mass, BMI, waist circumference, WHtR, and body fat percentage (all $p<0.05$). Changes were most pronounced in EX+GT, followed by EX, whereas the control group remained largely unchanged (Table 3 and Figure 2).

3.4.1. Body mass and BMI

Significant between-group differences were observed for BC and anthropometric outcomes. After adjustment for baseline values, ANCOVA indicated significant overall group effects for body mass ($F_{2,38}=6.74$, $p=0.003$, $\eta^2=0.26$) and BMI ($F_{2,38}=5.86$, $p=0.005$, $\eta^2=0.24$) (Table 3 and Figure 2).

3.4.2. Central adiposity

Significant between-group differences were also observed for central adiposity indices, including waist circumference ($F_{2,38}=8.90$, $p<0.001$, $\eta^2=0.32$) and WHtR ($F_{2,38}=7.31$, $p=0.002$, $\eta^2=0.28$) (Table 3 and Figure 2).

3.4.3. Body fat and fat-free mass

Body fat percentage demonstrated a significant overall group effect ($F_{2,38}=9.68$, $p<0.001$, $\eta^2=0.34$). In addition, although fat-free mass showed a small numerical increase in both exercise groups, the between-group difference was not statistically significant ($F_{2,38}=1.60$, $p=0.214$, $\eta^2=0.08$) (Table 3 and Figure 2).

The largest intervention effects were observed for body fat percentage ($\eta^2=0.34$) and waist circumference ($\eta^2=0.32$), representing large effect sizes, whereas body mass and BMI demonstrated moderate-to-large effects.

Table 3. Changes in body composition and anthropometric variables.

Variable	EX+GT	EX	CON	p	Partial η^2	95% CI (Adjusted Mean Difference vs CON)
Body Mass	73.8 $\pm$ 6.9 $\rightarrow$ 70.9 $\pm$ 6.4	72.6 $\pm$ 7.4 $\rightarrow$ 71.0 $\pm$ 7.0	74.1 $\pm$ 7.1 $\rightarrow$ 74.3 $\pm$ 7.3	0.003	0.26	-2.7 kg (-4.1 to -1.3)
BMI	25.9 $\pm$ 1.4 $\rightarrow$ 24.9 $\pm$ 1.3	25.7 $\pm$ 1.5 $\rightarrow$ 25.1 $\pm$ 1.4	26.0 $\pm$ 1.6 $\rightarrow$ 26.1 $\pm$ 1.6	0.005	0.24	-0.84 kg/m ² (-1.33 to -0.35)
Waist Circumference	88.4 $\pm$ 4.8 $\rightarrow$ 83.9 $\pm$ 4.4	87.9 $\pm$ 5.1 $\rightarrow$ 85.3 $\pm$ 4.8	88.8 $\pm$ 4.6 $\rightarrow$ 88.9 $\pm$ 4.8	<0.001	0.32	-3.9 cm (-5.5 to -2.3)
WHtR	0.52 $\pm$ 0.02 $\rightarrow$ 0.50 $\pm$ 0.02	0.52 $\pm$ 0.03 $\rightarrow$ 0.51 $\pm$ 0.02	0.53 $\pm$ 0.03 $\rightarrow$ 0.53 $\pm$ 0.03	0.002	0.28	-0.021 (-0.033 to -0.009)
Body fat (%)	29.8 $\pm$ 3.1 $\rightarrow$ 26.9 $\pm$ 2.8	29.4 $\pm$ 3.4 $\rightarrow$ 27.8 $\pm$ 3.1	30.1 $\pm$ 3.0 $\rightarrow$ 30.0 $\pm$ 3.2	<0.001	0.34	-2.5% (-3.6 to -1.4)
Fat-free Mass	51.8 $\pm$ 4.0 $\rightarrow$ 52.3 $\pm$ 4.1	51.3 $\pm$ 4.2 $\rightarrow$ 51.9 $\pm$ 4.1	51.5 $\pm$ 4.1 $\rightarrow$ 51.4 $\pm$ 4.2	0.214	0.08	0.4 kg (-0.3 to 1.1)

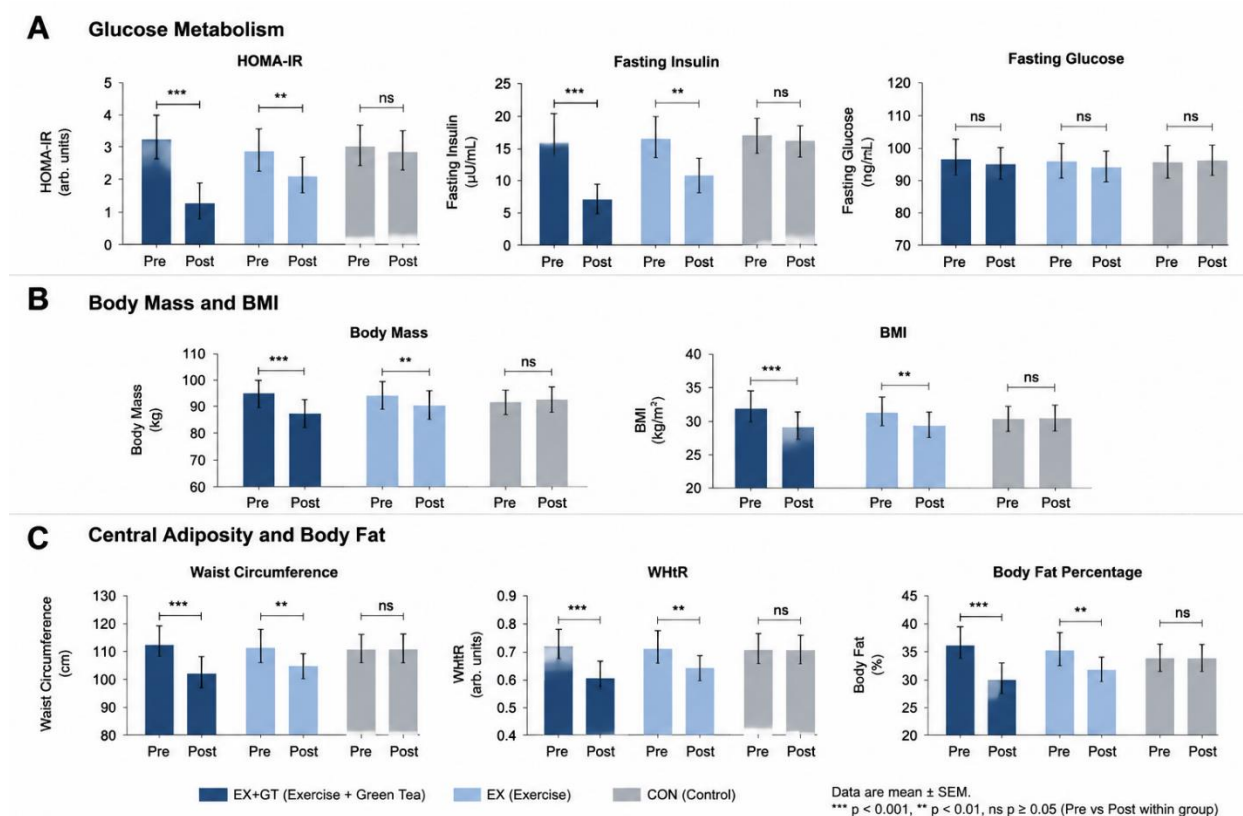


Figure 2. Effects of exercise interventions on glucose metabolism and body composition in the three study groups.

3.4.4. Pairwise Comparisons

Bonferroni-adjusted post hoc pairwise comparisons indicated that the EX+GT group achieved significantly greater improvements than the control group for HOMA-IR (adjusted $p < 0.001$), fasting insulin (adjusted $p < 0.001$), waist circumference (adjusted $p = 0.001$), WHtR (adjusted $p = 0.004$), body fat percentage (adjusted $p < 0.001$), body mass (adjusted $p = 0.006$), and BMI (adjusted $p = 0.009$). The EX-group also demonstrated significantly better outcomes than the control group for HOMA-IR (adjusted $p = 0.013$), fasting insulin (adjusted $p = 0.008$), waist circumference (adjusted $p = 0.017$), body fat percentage (adjusted $p = 0.011$), and WHtR (adjusted $p = 0.021$). When comparing the two exercise conditions, Bonferroni-adjusted pairwise comparisons demonstrated significantly greater reductions in HOMA-IR (adjusted $p = 0.041$) and waist circumference (adjusted $p = 0.038$) in the EX+GT group compared with the EX-group. No statistically significant between-group differences were observed for body mass, BMI, WHtR, body fat percentage, or fat-free mass following adjustment for multiple comparisons (all adjusted $p > 0.05$), although numerical improvements consistently favored the EX+GT intervention.

4. Discussion

This study examined whether a 12-week school-based bodyweight circuit training program, performed twice weekly, with or without daily green tea consumption, could improve IR and BC in sedentary overweight adolescent boys. The main finding was that HOMA-IR significantly decreased in both intervention

groups compared with controls, with the largest improvement in the combined EX+GT group, indicating that the combined intervention produced greater improvements in HOMA-IR than exercise alone. Although this pattern suggests a possible additive effect of green tea, the present study was not designed to determine whether the observed effects reflected true physiological synergy or the specific mechanisms responsible for these improvements. Secondary outcomes showed favorable changes in body mass, BMI, waist circumference, WHtR, and body fat percentage, while fat-free mass changed minimally and did not differ significantly between groups.

IR in adolescence is strongly linked to excess adiposity, particularly central fat accumulation, and reduced PA, and it represents an important early marker of cardiometabolic risk. In the present study, the reduction in HOMA-IR was driven primarily by decreases in fasting insulin, whereas fasting glucose changed only modestly. This pattern is consistent with the physiology of early metabolic improvement, where interventions often reduce compensatory hyperinsulinemia before large shifts in fasting glucose become evident (32).

The improvement observed in the EX-group supports the effectiveness of brief, scalable, school-based circuit training for enhancing insulin sensitivity in overweight youth. Even at a frequency of two sessions per week, the program likely increased skeletal muscle glucose uptake through exercise-induced adaptations such as enhanced insulin signaling, increased muscle oxidative capacity, improved mitochondrial function, and greater insulin sensitivity, all of which have been reported in previous

exercise studies (33). In addition, repeated bouts of moderate-to-vigorous activity may reduce low-grade inflammation and improve adipokine profiles, which can further contribute to improved insulin action.

Importantly, the EX+GT group demonstrated a significantly greater reduction in HOMA-IR than the EX-group. Although the present study was not designed to investigate mechanistic pathways, several biologically plausible explanations have been proposed in previous literature. Green tea contains catechins, particularly EGCG, which have been associated with improved insulin signaling, reduced oxidative stress, and modulation of glucose and lipid metabolism. These mechanisms may complement the metabolic adaptations induced by exercise; however, because biomarkers of oxidative stress, inflammation, endothelial function, or intracellular insulin signaling were not measured, the present findings cannot confirm that these pathways were responsible for the additional improvements observed.

Both intervention groups improved multiple anthropometric and BC indices, including waist circumference and WHtR, with the combined group generally showing the greatest magnitude of change. These outcomes are clinically relevant because central adiposity is more strongly associated with IR and cardiometabolic risk than BMI alone. The significant reductions in waist measures suggest that the intervention may have reduced abdominal fat accumulation or improved body fat distribution, even within a 12-week timeframe.

The finding that fat-free mass did not significantly increase is also notable. This observation suggests that the improvements in IR were achieved primarily through reductions in adiposity and improvements in metabolic function rather than increases in skeletal muscle mass. Such adaptations are commonly observed during relatively short exercise interventions in adolescents (15). Furthermore, bodyweight circuit training may improve muscular function and neuromuscular efficiency without producing large measurable increases in lean mass, particularly when training frequency is relatively low and dietary intake is not specifically designed to support muscle hypertrophy. In adolescents, growth and maturation also introduce variability that can make small changes in fat-free mass difficult to detect, especially using field methods commonly feasible in school settings (34). Thus, improvements in IR likely reflected qualitative metabolic adaptations and reductions in adiposity rather than substantial gains in lean tissue.

A key strength of this intervention is practicality. A 60-minute, twice-weekly, supervised circuit delivered at school minimizes barriers related to transportation, equipment access, and cost. This matters because adherence is often the limiting factor in adolescent lifestyle trials. The high session attendance observed in both exercise groups suggests that the program was feasible and acceptable for participants. From an implementation perspective, bodyweight circuits are attractive because they can be delivered in multipurpose spaces and adapted to different fitness levels through progression of rounds, work intervals, and exercise complexity. Nevertheless, successful implementation across different educational settings may depend on factors such as staff availability,

scheduling within the school curriculum, facility access, and institutional support.

The green tea component is also low-cost and relatively simple to implement. Although daily green tea consumption was feasible and demonstrated high compliance in the present study, compliance was assessed using self-reported daily logs and weekly monitoring, which may have introduced reporting bias. Therefore, larger placebo-controlled trials using more objective measures of compliance are needed before this approach can be recommended routinely as an adjunct strategy for improving metabolic health in adolescents.

The present findings align with evidence showing that structured exercise improves insulin sensitivity and adiposity-related markers in overweight adolescents. Circuit-style training, in particular, may be effective because it combines repeated whole-body muscular work with cardiovascular demand, increasing energy expenditure and stimulating favorable metabolic adaptations. The additional benefit seen with green tea is consistent with studies in other populations reporting modest improvements in metabolic outcomes with catechin-rich beverages, though results across trials are mixed and often depend on dose, duration, baseline metabolic risk, and adherence.

Strengths of this trial include the randomized controlled design, the inclusion of a clearly defined overweight adolescent population, the school-based delivery of the intervention, which enhances ecological validity, and the use of HOMA-IR as a prespecified primary outcome. Nevertheless, several limitations should be acknowledged. First, green tea intake was implemented without a placebo, limiting blinding and introducing the possibility of expectancy effects. Second, compliance with green tea consumption was assessed using self-reported logs, which are subject to reporting bias. Third, dietary intake was not tightly controlled, and participants' habitual PA outside the supervised intervention sessions was not objectively monitored; therefore, changes in energy intake or unsupervised PA may have influenced the observed outcomes. Fourth, BC assessment was performed using a field-based method, which is less precise than laboratory techniques such as dual-energy X-ray absorptiometry (DXA) and may have reduced sensitivity for detecting small changes in fat-free mass. Fifth, pubertal maturation was not assessed, although biological maturation can influence insulin sensitivity, BC, and responsiveness to exercise during adolescence. Sixth, the sample included only boys aged 14–17 years, limiting generalizability to girls or younger adolescents. Finally, the 12-week intervention provides only short-term evidence, and the durability of these improvements remains unknown. Future studies should consider including a green tea-only or placebo-controlled supplementation group to better isolate the independent effects of green tea, employing more precise BC techniques, objectively monitoring dietary intake and habitual PA, assessing pubertal maturation, and incorporating long-term follow-up to determine whether the observed metabolic improvements are maintained after the supervised intervention ends. Examining moderators such as baseline IR, pubertal stage, and intervention adherence may also help

identify which adolescents benefit most from this type of program.

4.1. Conclusion

In conclusion, a 12-week school-based bodyweight circuit training program significantly improved IR and several indices of BC in sedentary overweight adolescent boys. The combined exercise and green tea intervention produced greater improvements in HOMA-IR than exercise alone; however, additional placebo-controlled studies are required to determine whether green tea provides independent metabolic benefits beyond those achieved through exercise training. These findings indicate that a simple, low-cost, and feasible school-based intervention may improve markers associated with cardiometabolic health, particularly IR and central adiposity, in overweight adolescent boys. Overall, the present findings support school-based multicomponent lifestyle interventions as a practical strategy for improving insulin sensitivity and BC during adolescence.

Authors' Contribution: The author was responsible for the conception and planning of the study, methodological design, organization and implementation of the intervention, participant recruitment and assessment, data collection, statistical analysis, interpretation of the findings, and preparation and revision of the manuscript.

Funding Support: The study was conducted without financial support from governmental, institutional, commercial, or private funding sources.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process: The author declares that no generative artificial intelligence or AI-assisted technology was used in the preparation, writing, editing, or revision of this manuscript. The author assumes full responsibility for the accuracy, originality, integrity, and overall content of the published work.

Ethical Considerations: The research was conducted in accordance with the ethical principles of the Declaration of Helsinki. Appropriate measures were taken throughout participant recruitment, exercise training, green tea consumption, physical and biological assessments, and data management to protect the participants' privacy, dignity, safety, and well-being. Written informed consent was obtained from the parents or legal guardians of all participating adolescents before enrollment. The adolescents were provided with age-appropriate information about the study procedures and were informed that participation was voluntary.

Data Availability: The data generated and analyzed in this study are available from the corresponding author upon reasonable request, subject to applicable privacy and confidentiality requirements.

Acknowledgments: The author gratefully acknowledges the participating adolescents, their parents or legal guardians, and the school personnel who supported the implementation of the study.

Conflicts of Interest: The author declares that there are no financial, personal, or professional conflicts of interest associated with this research.

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