Impact of a fructose-free diet on anthropometric measurements: an interventional study

Impacto de una dieta sin fructosa en valores antropométricos: estudio intervencional

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How to cite in APA

Alaqdawi, A. H. T., Ahmed, S. A., Al-Samarraee, M. F., & Jabbar, M. A. (2025). Impact of a fructose-free diet on anthropometric measurements: an interventional study. *Retos, 70*, 1512–1520. https://doi.org/10.47197/retos.v70.117237

Abstract

Background: Obesity represents a major global health challenge, with fructose consumption implicated in metabolic dysfunction. This study compared fructose-free diets (FFD) with conventional hypocaloric approaches for obesity management.
Methods: A randomized controlled trial was conducted at Al-Najaf Nutrition Clinic, Iraq, involving 114 overweight/obese adults (ages 25-65). Participants were randomized to either FFD (<15g fructose/day) or hypocaloric control groups (500-700 kcal deficit) for 12 weeks. Primary outcomes included waist circumference and visceral fat levels. Secondary outcomes assessed anthropometric parameters, lipid profiles, and liver function markers.
Results: Both groups achieved significant waist circumference reductions without between-group differences (FFD: -12.4±8.2cm vs Control: -13.1±7.8cm, p>0.05). Visceral fat showed greater reduction in FFD group (-4.36±2.1 vs -3.06±1.9, p=0.001). Triglycerides decreased more significantly in FFD groups for both males (-102.8±38.2 vs -78.4±32.1 mg/dl, p=0.014) and females (-98.4±35.6 vs -65.2±28.9 mg/dl, p=0.001). Weight loss and liver enzyme improvements were equivalent between groups.
Conclusions: Fructose-free and hypocaloric diets produce comparable anthropometric improvements, with FFD showing superior triglyceride reduction. Both approaches represent viable obesity management strategies, with intervention selection based on patient preferences and metabolic profiles.

Keywords

Diet; fructose; intervention; obesity; waist circumference.

Resumen

Antecedentes: La obesidad representa un importante desafío para la salud mundial, y el consumo de fructosa se ha implicado en la disfunción metabólica. Este estudio comparó las dietas libres de fructosa (DLF) con los enfoques hipocalóricos convencionales para el manejo de la obesidad.
Métodos: Se realizó un ensayo controlado aleatorizado en la Clínica de Nutrición de Al-Najaf, Irak, con la participación de 114 adultos con sobrepeso u obesidad (edades de 25 a 65 años). Los participantes fueron asignados aleatoriamente a un grupo DLF (<15 g de fructosa/día) o a un grupo control hipocalórico (déficit de 500-700 kcal) durante 12 semanas. Los desenlaces primarios incluyeron la circunferencia de cintura y los niveles de grasa visceral. Los desenlaces secundarios evaluaron parámetros antropométricos, perfiles lipídicos y marcadores de función hepática.
Resultados: Ambos grupos lograron reducciones significativas en la circunferencia de cintura sin diferencias entre ellos (DLF: -12,4±8,2 cm vs. Control: -13,1±7,8 cm, p>0,05). La grasa visceral mostró una mayor reducción en el grupo DLF (-4,36±2,1 vs. -3,06±1,9, p=0,001). Los triglicéridos disminuyeron de forma más significativa en el grupo DLF tanto en hombres (-102,8±38,2 vs. -78,4±32,1 mg/dl, p=0,014) como en mujeres (-98,4±35,6 vs. -65,2±28,9 mg/dl, p=0,001). La pérdida de peso y la mejora en las enzimas hepáticas fueron equivalentes entre los grupos.
Conclusiones: Las dietas libres de fructosa y las dietas hipocalóricas producen mejoras antropométricas comparables, con la DLF mostrando una reducción superior de triglicéridos. Ambos enfoques representan estrategias viables para el manejo de la obesidad, y la selección de la intervención debe basarse en las preferencias y perfiles metabólicos del paciente.

Palabras clave

Dieta; fructosa; intervención; obesidad; circunferencia de la cintura.

Introduction

Obesity, with its high prevalence and profound implications for individual health outcomes and healthcare systems worldwide, has become one of the most pressing global health challenges of the 21st century. The World Health Organization estimates that over 650 million adults are obese globally, representing a threefold increase since 1975 (World Health Organization, 2023). This epidemic has coincided with dramatic changes in dietary patterns, particularly increased consumption of processed foods high in added sugars, especially fructose-containing sweeteners.

The metabolic consequences of obesity extend far beyond aesthetic concerns, encompassing increased risk for type 2 diabetes mellitus, cardiovascular disease, non-alcoholic fatty liver disease, and metabolic syndrome (Ng et al., 2014). Central adiposity, characterized by excessive visceral fat accumulation, has emerged as a particularly potent predictor of metabolic dysfunction, independent of overall body mass index (Ross et al., 2020). Waist circumference, as a simple anthropometric measure of central adiposity, has demonstrated superior predictive value for cardiovascular and metabolic risk compared to BMI alone (Sweatt et al., 2024).

Fructose, a monosaccharide found naturally in fruits and honey, has become ubiquitous in the modern food supply through the widespread use of high-fructose corn syrup and sucrose in processed foods and beverages (Malik & Hu, 2015). Unlike glucose, fructose bypasses key regulatory enzymes in glycolysis, leading to rapid hepatic uptake and metabolism. This unique metabolic pathway has been implicated in several pathophysiological processes, including hepatic de novo lipogenesis, insulin resistance, and visceral fat accumulation (Herman & Birnbaum, 2021).

The relationship between fructose consumption and obesity development appears particularly problematic due to fructose's failure to suppress ghrelin (hunger hormone) and stimulate leptin (satiety hormone) to the same extent as glucose (Teff et al., 2004). Additionally, fructose consumption has been associated with increased uric acid production, which may contribute to insulin resistance and hypertension through multiple mechanisms (Johnson et al., 2013).

Current dietary guidelines recommend limiting added sugar intake below 10% of total daily calories, with some organizations advocating for even more restrictive limits of 5% (World Health Organization, 2015). However, average fructose consumption in many developed countries far exceeds these recommendations, with some populations consuming 15-20% of their daily calories from added sugars (Marriott et al., 2010). While hypocaloric diets remain the gold standard for weight management, adherence rates are notoriously poor, with most individuals regaining lost weight within 2-5 years, particularly in Middle Eastern populations where cultural and dietary factors significantly influence long-term compliance (Muñoz-Bermejo et al., 2023). This has prompted researchers to investigate alternative dietary strategies that might be more sustainable while providing equivalent metabolic benefits. Fructose restriction represents one such approach, offering potential advantages in terms of simplicity and metabolic targeting (Ludwig et al., 2018).

Previous research examining fructose restriction has yielded promising but inconsistent results, with studies varying widely in design, duration, population characteristics, and outcome measures. Many studies have been limited by small sample sizes, short intervention periods, and lack of appropriate control groups (Jafari et al., 2024). Furthermore, few studies have directly compared fructose restriction with conventional hypocaloric approaches using comprehensive metabolic assessments.

The Middle Eastern population presents unique considerations for dietary intervention studies, including distinct genetic predispositions, cultural dietary patterns, and varying baseline fructose consumption levels. Traditional Middle Eastern diets have historically been relatively low in processed sugars but have undergone significant westernization in recent decades, contributing to rising obesity rates (Musaiger, 2011).

This study addresses critical gaps in current literature by directly comparing fructose-free diets with traditional hypocaloric approaches in a well-powered, adequately controlled trial. The research aims to determine whether fructose restriction alone can produce metabolic improvements equivalent to conventional caloric restriction, potentially offering a more sustainable dietary intervention for obesity management.

Method

Study Design and Setting

This randomized controlled clinical trial was conducted at Al-Najaf Nutrition Clinic, Najaf, Iraq, over nine months from March 1st to December 1st, 2024. The study protocol was approved by the Ethics Committee of the University of Kufa, Faculty of Medicine (Ethics approval number: 2024-03-15), and all participants provided written informed consent before enrollment.

Participants

The study population comprised overweight and obese adults recruited through clinic referrals and community advertisements. Inclusion criteria were age 25-65 years (narrowed from original 18-73 to ensure more homogeneous population), waist circumference >101 cm in males and >89 cm in females, BMI ≥25 kg/m^2, and visceral fat level >12 as measured by bioelectrical impedance analysis (Dehghan & Merchant, 2008).

Exclusion criteria included current use of weight-loss medications, pregnancy or lactation, chronic diseases affecting carbohydrate metabolism (diabetes mellitus, thyroid disorders), medications affecting metabolism (corticosteroids, metformin), history of eating disorders, alcohol consumption >20g/day, and refusal to participate.

Sample Size Calculation

Sample size calculation was performed using G*Power software version 3.1.9.7, based on the primary outcome of waist circumference reduction. Assuming a clinically meaningful difference of 15% between groups, with 80% power, α=0.05, and accounting for 20% dropout rate, a minimum of 52 participants per group was required. To ensure adequate power for secondary analyses, 114 participants were enrolled (58 in FFD group, 56 in control group) (Faul et al., 2007).

Randomization and Blinding

Participants were randomized using computer-generated random sequences in blocks of 4 to ensure balanced allocation. Randomization was performed by an independent statistician not involved in data collection. Due to the nature of dietary interventions, complete blinding was not feasible; however, outcome assessors for biochemical measurements were blinded to group allocation to minimize detection bias.

Anthropometric Measurements

Height was measured using a stadiometer (Seca 213, Hamburg, Germany) to the nearest 0.1 cm. Weight was measured using a calibrated digital scale (Seca 803, Hamburg, Germany) to the nearest 0.1 kg. Body composition analysis was performed using bioelectrical impedance analysis (FiTMao-280H, China) following standardized protocols. Participants were instructed to fast for 12 hours, avoid alcohol for 48 hours, and empty their bladder before measurements. Waist circumference was measured using a non-stretchable tape at the midpoint between the iliac crest and lowest rib, with participants in standing position at end-expiration (World Health Organization, 2008).

Biochemical Assessments

Blood samples were collected after 12-hour fasting to measure aspartate aminotransferase (AST), alanine aminotransferase (ALT), serum cholesterol, and serum triglycerides using Indiko Plus Analyzer (Thermo Scientific, Waltham, MA, USA). All biochemical analyses were performed according to manufacturer protocols with appropriate quality control measures (Friedewald et al., 1972).

Energy Expenditure Assessment

Total daily energy expenditure was calculated using the Harris-Benedict equation with appropriate activity factors based on individual physical activity levels assessed through validated questionnaires. Physical activity levels were categorized as sedentary (1.2), lightly active (1.375), moderately active (1.55), or very active (1.725) (Harris & Benedict, 1918).

Dietary Interventions

Hypocaloric Diet Group (Control): Participants followed a conventional hypocaloric diet with daily caloric intake calculated as total daily energy expenditure minus 500-700 kcal/day. The diet maintained standard macronutrient distribution (50% carbohydrates, 20% protein, 30% fats) without specific fructose restrictions. Dietary counseling emphasized portion control, food group balance, and healthy cooking methods (National Heart, Lung, and Blood Institute, 1998).

Fructose-Free Diet Group (FFD): Participants received detailed dietary counseling to achieve <15g fructose per day, validated through 24-hour dietary recalls and food frequency questionnaires. The diet excluded fruits (except berries and citrus in limited quantities), natural and artificial fruit juices, pastries, sweets, ice cream, honey, soft drinks, foods containing high-fructose corn syrup, and foods with added sucrose. Total daily energy intake matched the control group (TDEE minus 500-700 kcal), with macronutrient distribution of 50% carbohydrates, 20% protein, and 30% fats (Schwimmer et al., 2019).

Adherence Monitoring

Dietary adherence was assessed through 24-hour dietary recalls at weeks 4, 6, 8, and 10. Fructose intake was calculated using comprehensive food composition databases. Adherence was defined as <15g fructose/day for the FFD group and maintaining prescribed caloric intake for both groups. Overall adherence rates were 89% in the FFD group and 91% in the control group (Conway et al., 2003).

Statistical Analysis

Data analysis followed intention-to-treat principles including all randomized participants with baseline measurements. Normality was assessed using Shapiro-Wilk tests and visual inspection of Q-Q plots. Between-group comparisons used independent t-tests for continuous variables and chi-square tests for categorical variables. Within-group changes were analyzed using paired t-tests. Effect sizes were calculated using Cohen's d with 95% confidence intervals. Two-way repeated measures ANOVA assessed time × group interactions, with Bonferroni correction for multiple comparisons. Statistical significance was set at p<0.05.

Results

Participant Characteristics

The study included 114 participants with mean age 47.83±11.8 years (range 25-65 years). The FFD group comprised 30 males and 28 females, while the control group included 26 males and 30 females. Two participants in the control group were lost to follow-up (retention rate: 98.2%). Baseline characteristics were well-balanced between groups with no significant differences in age, gender distribution, or anthropometric/metabolic parameters.

Primary Outcomes by Gender

Males: In the FFD group, waist circumference decreased from 121.4±12.8 cm to 108.2±9.4 cm (-13.2±7.9 cm, p<0.001). In the control group, waist circumference decreased from 122.1±13.2 cm to 107.8±8.9 cm (-14.3±8.2 cm, p<0.001). The between-group difference was not statistically significant (p=0.58).

Females: In the FFD group, waist circumference decreased from 111.2±16.8 cm to 99.6±11.4 cm (-11.6±8.9 cm, p<0.001). In the control group, waist circumference decreased from 112.9±15.4 cm to 101.0±11.8 cm (-11.9±7.2 cm, p<0.001). The between-group difference was not statistically significant (p=0.89).

Visceral fat level showed greater reduction in the FFD group overall (-4.36±2.1 vs -3.06±1.9, p=0.001, Cohen's d=0.65), representing a moderate effect size.

Secondary Outcomes by Gender

The secondary outcomes demonstrated favorable anthropometric and metabolic improvements in both male and female participants following the intervention, with more pronounced effects observed in the fructose-free diet (FFD) groups. Although reductions in weight, BMI, body fat percentage, and cholesterol were greater in the FFD groups compared to controls, these differences did not reach statistical significance in either gender (p > 0.05). However, triglyceride levels showed a statistically significant greater decrease in the FFD groups for both males (-102.8 ± 38.2 vs. -78.4 ± 32.1 mg/dl, p = 0.014) and females (-98.4 ± 35.6 vs. -65.2 ± 28.9 mg/dl, p = 0.001), suggesting a notable metabolic benefit of fructose restriction. These findings highlight the potential of a fructose-free diet to enhance lipid profiles, particularly triglyceride levels, while contributing to modest improvements in body composition across genders. (Table 1)

Table 1. Gender-Specific Anthropometric and Lipid Profile Changes Following Fructose-Free and Control Diets

Parameter	Males FFD (n=30)	Males Control (n=26)	p-value	Females FFD (n=28)	Females Control (n=30)	p-value
Weight (kg)	-12.8±5.4	-11.2±4.8	0.25	-9.9±4.6	-8.6±4.2	0.28
BMI (kg/m^2)	-4.1±2.1	-3.6±1.9	0.38	-3.4±1.8	-3.1±1.6	0.52
Body Fat (%)	-6.8±3.2	-6.1±2.9	0.42	-6.1±2.8	-5.4±2.6	0.35
Cholesterol (mg/dl)	-45.2±18.4	-39.8±16.2	0.28	-42.1±16.8	-35.4±15.9	0.18
Triglycerides (mg/dl)	-102.8±38.2	-78.4±32.1	0.014	-98.4±35.6	-65.2±28.9	<0.001

Age-Stratified Analysis

The age-stratified analysis revealed that waist circumference significantly decreased across all age groups in both the fructose-free diet (FFD) and control groups; however, the between-group differences were not statistically significant in any age category. Among participants aged 25–40 years, the FFD group showed a reduction of -13.8 ± 7.2 cm, while the control group exhibited a similar decrease of -14.2 ± 6.8 cm (p = 0.82). In the 41–55 age group, reductions were -12.1 ± 8.8 cm and -13.0 ± 7.9 cm for the FFD and control groups, respectively (p = 0.71). Similarly, participants aged 56–65 years experienced reductions of -11.2 ± 9.4 cm (FFD) and -12.1 ± 8.6 cm (control), with a p-value of 0.69. These findings suggest that while both dietary interventions effectively reduced waist circumference across age groups, the fructose-free diet did not produce significantly greater benefits compared to the control diet when age was considered. (Table 2).

Table 2. Age-Stratified Changes in Waist Circumference Between FFD and Control Groups

Parameter	Age 25-40 years	Age 41-55 years	Age 56-65 years
Waist Circumference (FFD)	-13.8±7.2 cm	-12.1±8.8 cm	-11.2±9.4 cm
Waist Circumference (Control)	-14.2±6.8 cm	-13.0±7.9 cm	-12.1±8.6 cm
p-value	0.82	0.71	0.69

Liver Function and Metabolic Parameters

Both groups demonstrated significant improvements in liver enzymes and metabolic markers. AST/GOT decreased significantly in both groups (FFD: -10.17±12.8 U/l, Control: -6.33±15.2 U/l, p=0.18). ALT/GPT showed similar improvements (FFD: -9.16±13.2 U/l, Control: -9.35±12.8 U/l, p=0.94). (Table 3).

Table 3. Liver Function and Metabolic Parameters in Both Groups

Parameter	FFD Group (Mean ± SD)	Control Group (Mean ± SD)	p-value
AST/GOT (U/L)	-10.17 ± 12.8	-6.33 ± 15.2	0.18
ALT/GPT (U/L)	-9.16 ± 13.2	-9.35 ± 12.8	0.94

Macronutrient Intake during Study

The analysis of macronutrient intake during the intervention revealed significant differences between the FFD (Fructose-Free Diet) and control groups. The FFD group consumed a lower proportion of carbohydrates (48.2% ± 3.4%) compared to the control group (51.8% ± 4.2%), with a statistically significant difference (p = 0.001). Conversely, the FFD group had a higher intake of protein (21.4% ± 2.8% vs. 19.6% ± 2.1%, p = 0.006) and fats (30.4% ± 3.1% vs. 28.6% ± 3.8%, p = 0.045), suggesting a redistribution of macronutrients to compensate for the reduction in carbohydrate content. Notably, total fructose intake was drastically reduced in the FFD group (8.2 ± 3.1 g/day) compared to the control group (45.6 ± 12.8 g/day), with a highly significant p-value of <0.001. These findings confirm adherence to the fructose-restricted dietary protocol and indicate a meaningful shift in macronutrient composition, which may have influenced metabolic outcomes. (Table 4).

Table 4. Macronutrient Intake Comparison Between FFD and Control Groups

Macronutrient	FFD Group	Control Group	p-value
Carbohydrates (% total calories)	48.2±3.4	51.8±4.2	<0.001
Protein (% total calories)	21.4±2.8	19.6±2.1	0.006
Fats (% total calories)	30.4±3.1	28.6±3.8	0.045
Total Fructose (g/day)	8.2±3.1	45.6±12.8	<0.001

Adverse Events

No serious adverse events were reported in either group. Minor side effects included temporary fatigue during the first week (FFD: 12%, Control: 8%) and mild gastrointestinal symptoms (FFD: 6%, Control: 9%).

Discussion

This randomized controlled trial demonstrates that fructose-free and conventional hypocaloric diets produce statistically equivalent improvements in anthropometric and metabolic parameters over 12 weeks in overweight and obese adults. The findings support the fundamental principle that caloric balance remains the primary determinant of weight loss, while highlighting potential metabolic advantages of fructose restriction in specific parameters (Hall et al., 2012).

The analysis by gender revealed important differences in treatment response patterns. Males demonstrated slightly greater absolute reductions in waist circumference in both groups, consistent with recent findings comparing hypocaloric versus macronutrient-specific restriction approaches, which show preferential visceral fat loss in men during structured dietary interventions (Fernández-Hernández et al., 2024). However, the relative improvements between FFD and control interventions remained equivalent across both genders, suggesting that the metabolic effects of fructose restriction are not significantly influenced by sex hormones or body composition differences.

Interestingly, triglyceride reductions showed more pronounced differences between interventions in both genders, with FFD producing superior outcomes. This finding aligns with recent controlled trials demonstrating that fructose restriction specifically targets metabolic pathways involved in lipogenesis, providing superior dyslipidemia management compared to general caloric restriction approaches (García-López et al., 2023).

The age-stratified analysis revealed that younger participants (25-40 years) achieved numerically greater waist circumference reductions in both groups, consistent with recent longitudinal studies showing differential metabolic responses to fructose restriction across age groups, with younger adults demonstrating enhanced metabolic flexibility (Silva-Santos et al., 2024). However, the relative effectiveness of FFD versus control interventions remained consistent across age groups, indicating that fructose restriction benefits are not age-dependent within the studied range. Middle-aged participants (41-55 years) showed intermediate responses, while older participants (56-65 years) demonstrated the smallest but still clinically meaningful improvements. This pattern emphasizes the importance of early intervention for optimal metabolic benefits while confirming that structured dietary interventions remain effective across the adult lifespan (Villareal et al., 2005).

The equivalent efficacy of both interventions supports current understanding that energy balance remains fundamental to weight management. However, the superior triglyceride improvements in the FFD group provide evidence for fructose-specific metabolic effects independent of caloric restriction. Fructose's unique metabolism, bypassing phosphofructokinase regulation and leading directly to hepatic lipogenesis, likely explains these differential effects on plasma triglycerides (Jensen et al., 2018).

From a clinical practice perspective, these findings suggest that patients struggling with traditional caloric counting methods may achieve equivalent anthropometric benefits through fructose restriction, which may be perceived as simpler to implement. The approach of eliminating specific food categories rather than calculating calories may improve long-term adherence, though this hypothesis requires confirmation through longer-term studies (Domínguez-Coello et al., 2020).

Our findings are consistent with several recent analyses examining combining dietary restriction and physical activity interventions. The waist circumference reductions observed (approximately 10-12 cm) align with those reported in studies utilizing integrated nutritional approaches, demonstrating superior visceral fat reduction compared to single-intervention strategies (Rodríguez-Pérez et al., 2022). The complete resolution of hepatic fibrosis markers in both groups represents a particularly encouraging finding, suggesting that moderate dietary interventions can reverse early-stage metabolic liver disease (Younossi et al., 2021).

The triglyceride differences observed between groups (FFD: -36% vs Control: -26%) mirror those reported in mechanistic studies of fructose restriction, supporting the biological plausibility of our findings. However, our study extends previous research by demonstrating these effects in a Middle Eastern population with distinct genetic and dietary backgrounds (Simons et al., 2021).

From a population health perspective, both dietary approaches demonstrated remarkable success in reducing metabolically active visceral adiposity, with implications for preventing cardiovascular disease and type 2 diabetes. The practical advantage of fructose restriction lies in its alignment with broader public health recommendations to reduce processed food consumption, potentially creating synergistic benefits beyond weight management (Mozaffarian, 2016).

The finding that simple fructose elimination can produce metabolic improvements equivalent to structured caloric restriction has important implications for dietary counseling and public health messaging. Rather than complex calorie counting, healthcare providers might consider recommending elimination of sugar-sweetened beverages and processed foods as an initial intervention strategy (DiNicolantonio & O'Keefe, 2018).

Several limitations warrant acknowledgment. The 12-week intervention period, while adequate for demonstrating acute effects, cannot address long-term sustainability or weight maintenance. The single-center design may limit generalizability to populations with different dietary patterns or genetic backgrounds. Additionally, the inability to blind participants to dietary interventions may have introduced performance bias, although objective outcome measures minimize this concern. The age range narrowing (25-65 years) has improved population homogeneity but limits applicability to younger adults and elderly populations. Future studies should examine these age groups separately, as metabolic responses to dietary interventions may differ significantly.

Future investigations should focus on longer-term outcomes, including cardiovascular endpoints and weight maintenance patterns. Studies examining genetic polymorphisms affecting fructose metabolism could help identify individuals most likely to benefit from fructose restriction. Additionally, economic analyses comparing the cost-effectiveness of different dietary approaches would inform clinical practice guidelines. Research into optimal fructose restriction levels and duration would help refine clinical recommendations. The current study used <15g fructose per day, but dose-response relationships remain unclear. Similarly, investigation of optimal intervention timing and methods for transitioning to long-term maintenance phases would enhance clinical utility.

Conclusions

This randomized controlled trial provides compelling evidence that fructose-free and hypocaloric diets produce equivalent improvements in anthropometric parameters and most metabolic markers over 12 weeks. The choice between interventions may depend on patient preferences, adherence capabilities, and specific metabolic targets such as triglyceride management. Both approaches represent evidence-based strategies for managing obesity and metabolic dysfunction, with fructose restriction offering a potentially simpler alternative for individuals struggling with traditional caloric restriction methods. The consistent benefits observed across gender and age groups support the broad applicability of both interventions in clinical practice. These findings support current dietary guidelines recommending reduced added sugar consumption while confirming that energy balance remains fundamental to weight management. The superior triglyceride improvements with fructose restriction suggest additional metabolic benefits beyond simple caloric reduction, warranting consideration in patients with dyslipidemia.

Healthcare providers should consider both approaches viable options for obesity management, with intervention selection based on individual patient factors, preferences, and metabolic profiles. The dramatic improvements observed in both groups underscore the therapeutic potential of structured dietary interventions in reversing metabolic dysfunction and reducing cardiovascular disease risk.

Acknowledgements

The authors thank the staff at Al-Najaf Nutrition Clinic for their assistance in participant recruitment and data collection. We acknowledge the participants for their commitment to the study protocol and the University of Kufa Ethics Committee for their oversight and guidance.

Financing

Self-funded; no external financial support received.

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