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How do meal timing and meal frequency influence the development, prevention, and management of metabolic syndrome? A systematic review of human studies

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ABSTRACT

Background: Metabolic syndrome (MetS) is a complex condition characterized by central obesity, insulin resistance, hypertension, and dyslipidemia, significantly raising the risk for chronic diseases such as cardiovascular disease and type 2 diabetes. Recent research emphasizes meal timing and frequency as potentially modifiable lifestyle factors influencing metabolic health independently of caloric intake.

Objective: To systematically review how meal timing and meal frequency impact the development, prevention, and management of metabolic syndrome.

Methods: A comprehensive search across Semantic Scholar, Google Scholar, and Scopus extensive academic database, identified relevant literature. Studies were included if they assessed meal timing/frequency interventions in adults, reported metabolic syndrome components, involved human subjects, and lasted at least four weeks. Data extraction systematically focused on study design, participant characteristics, intervention specifics, and metabolic outcomes.

Results: Thirty-two studies were reviewed, comprising randomized controlled trials, cohort studies, meta-analyses, and intervention studies. Key findings indicate that regular and early time-restricted eating significantly improves insulin sensitivity, glucose metabolism, lipid profiles, and body composition (e.g., reduced visceral fat and waist circumference). Conversely, irregular or infrequent eating patterns, such as one meal per day, are associated with negative outcomes, including elevated blood pressure and cholesterol levels.

Conclusions: Aligning meal timing and frequency with circadian rhythms and maintaining consistent meal schedules notably enhances metabolic health markers. These findings provide strong support for incorporating chrononutrition principles into public health recommendations and clinical practices for managing metabolic syndrome.

KEYWORDS

Body composition, Circadian rhythms, Insulin sensitivity, Meal frequency, Meal timing, Metabolic syndrome, Time-restricted eating, Type 2 diabetes.

INTRODUCTION

Metabolic syndrome represents a complex and pervasive public health challenge, characterized by a constellation of interconnected physiological and biochemical abnormalities, including central obesity, hypertension, dyslipidemia, and impaired glucose tolerance[1]. This syndrome is not merely a collection of symptoms but a significant risk factor for the development of severe chronic non-communicable diseases, most notably cardiovascular disease and type 2 diabetes. The escalating global prevalence of metabolic syndrome underscores an urgent need for a deepened understanding of its multifactorial etiology and the identification of effective, scalable interventions for both its prevention and management[2].

Conventional strategies for addressing metabolic syndrome typically encompass a multifaceted approach that combines pharmacological treatments with foundational lifestyle modifi-

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cations. These lifestyle interventions primarily involve dietary adjustments and recommendations for increased physical activity, aiming to improve individual metabolic parameters and reduce overall disease burden[3]. While these established methods have demonstrated efficacy in mitigating the progression of metabolic syndrome, their implementation often faces challenges related to patient adherence and long-term sustainability, highlighting the imperative for exploring complementary or alternative strategies that could enhance their impact.

In recent years, scientific inquiry has increasingly shifted focus beyond the macronutrient composition of diets to the temporal aspects of food intake—specifically, meal timing and frequency. This emerging paradigm recognizes that *when* and *how often* an individual eats can exert profound effects on metabolic processes, independent of total caloric intake. Studies suggest that maintaining consistent meal schedules, particularly those that front-load energy intake earlier in the day, can optimize glucose regulation, enhance insulin sensitivity, and modulate other crucial metabolic markers[4,5]. However, a comprehensive and synthesized understanding of these temporal dietary patterns in the context of metabolic syndrome remains crucial for clinical application.

Despite the growing recognition of chrononutrition's potential, a clear, unified picture of how specific meal timing and frequency patterns directly influence the development, prevention, and management of metabolic syndrome is still evolving. There is a discernible research gap in systematically consolidating the evidence across diverse study designs and populations. Therefore, this paper aims to address this gap by conducting a comprehensive review of the existing literature. Our primary objective is to elucidate the specific effects of meal timing and meal frequency on key metabolic syndrome outcomes, thereby contributing to evidence-based recommendations for improved public health interventions.

METHODOLOGY

To comprehensively investigate the influence of meal timing and frequency on the development, prevention, and management of metabolic syndrome, a systematic search was executed across the extensive Semantic Scholar corpus, Google Scholar, and Scopus, encompassing over 126 million academic papers. This initial broad search strategy was designed to capture a wide array of relevant literature, resulting in the retrieval of 500 papers identified as most pertinent to the core research question. Subsequent to the initial retrieval, a rigorous screening process was implemented to ensure the inclusion of only high-quality and directly relevant studies. The predefined inclusion criteria for this screening phase were multifaceted: studies must have examined meal timing and/or frequency interventions (e.g., time-restricted feeding, intermittent fasting, meal spacing, specific number of meals per day); all study participants must have been adults (aged 18 years or older); the studies were required to measure at least one component of metabolic syndrome (e.g., hypertension, dyslipidemia, insulin resistance, central obesity); eligible study designs included intervention studies (randomized controlled trials, quasi-experimental designs), prospective cohort studies, or systematic reviews/meta-analyses; the intervention or follow-up duration needed to be a minimum of four weeks; studies had to be conducted in human subjects; and the intervention's focus needed to extend beyond mere caloric restriction to include timing or frequency components. Additionally, participants were required to be free from severe medical conditions that could independently confound metabolic outcomes. Each screening question was carefully considered in conjunction with the others to make a holistic judgment on a paper's suitability for inclusion.

Data extraction from the selected papers was systematically performed utilizing a large language model, which was meticulously guided by precise, pre-defined instructions for each data column. The model was provided with pre-defined instructions specifying: (1) identification of study design (e.g., randomized controlled trial, cohort, intervention, or meta-analysis); (2) extraction of participant characteristics (sample size, age range, sex ratio, and inclusion/exclusion criteria); (3) description of meal timing or frequency intervention (type, duration, timing schedule, and number of meals per day); and (4) extraction of primary metabolic outcomes (body weight, glucose metabolism, insulin sensitivity, lipid profile, and blood pressure). The outputs were subsequently verified manually by two independent reviewers for accuracy and completeness. To ensure data validity and reproducibility, a manual review by two independent researchers was conducted on all extracted data entries. The human reviewers cross-verified the model's outputs against the original publications to confirm accuracy, completeness, and proper contextual interpretation of study parameters. Any discrepancies between the model output and the source text were corrected manually, and consensus was reached through discussion. For every included study, the model was tasked with specifying the exact study design, differentiating between randomized controlled trials, cohort studies, cross-sectional studies, and intervention studies, with particular attention paid to descriptions within the methods section. In instances where the design was not explicitly stated, the methodology was thoroughly reviewed to determine the most appropriate classification, and any multiple design elements were comprehensively listed. Participant characteristics, extracted primarily from "Participants" or "Subjects" sections, included the total number of participants, age range or mean age, gender distribution, specific health status or metabolic conditions (e.g., metabolic syndrome, obesity, diabetes risk), and clear inclusion/exclusion criteria. Missing participant information was explicitly noted. Details of meal timing and frequency interventions were extracted from the methods section, focusing on precise descriptions of protocols, such as the number of meals per day, specific meal timings (e.g., hours or relative to circadian rhythms), intervention duration, and any unique instructions regarding meal consumption. For studies comparing multiple groups, details for each were extracted separately. Finally, primary metabolic outcomes, including body weight changes, glucose metabolism markers, insulin sensitivity, lipid profile, and blood pressure, were extracted from the results section, emphasizing statistically significant findings, specific measurement values, statistical significance (p-values), and measurement units.

RESULTS

Characteristics of Included Studies

The analysis of the included studies reveals a diverse landscape of research designs and participant populations exploring the impact of meal timing and frequency on metabolic health. Out of the 32 studies analyzed, the majority, 22, were randomized controlled trials (RCTs), including both crossover and parallel designs. Additionally, four cohort studies, four intervention studies, three meta-analyses, and two pilot trials were identified. This variety in study designs indicates a ro-

Table 1. Characteristics of Included Studies

Study	Study Design	Population Characteristics	Intervention Type (Timing or Frequency)	Primary Outcomes
Allison et al., 2020 (6)	Randomized controlled trial with crossover design	12 healthy adults, mean age 26.3 ± 3.4 years, BMI 19-27 kg/m2	Daytime (08.00-19.00h) vs. Delayed (12.00-23.00h) eating schedule	Body weight, glucose metabolism, insulin sensitivity, lipid profile
Blazey et al., 2023 (7)	Systematic review and meta-analysis of randomized controlled trials	Adults aged 18 years, healthy, overweight, and obese	Low (3 meals/day) vs. High (4 meals/day) eating frequency	Body weight, Body Mass Index (BMI), glucose metabolism, lipid profile
Dedov et al., 2021 (8)	Intervention study	77 patients with metabolic syndrome, 32 men and 45 women	3 meals/day at specific times (7-9 am, 1-2 pm, 6-7 pm)	Body Mass Index (BMI), body fat, insulin sensitivity (Homeostatic Model Assessment of Insulin Resistance (HOMA-IR))
Grangeiro et al., 2020 (9)	Randomized controlled trial with parallel design	40 women with obesity	6 meals/day vs. 3 meals/day	Body weight, glucose metabolism, insulin sensitivity, lipid profile
Guo et al., 2020 (10)	Randomized controlled trial	39 patients with metabolic syndrome, aged 30-50 years	8 weeks of "two-day" modified intermittent fasting	Fat mass
He et al., 2022 (11)	Randomized controlled trial	Participants with metabolic syndrome	8-hour time-restricted eating schedule	Body weight, visceral fat, fasting glucose, lipid profile
Kessler et al., 2020 (12)	Randomized controlled trial with crossover design	29 non-diabetic men, mean age 45.9±2.5 years	High-carb meal at 09:00 and high-fat meal at 15:40, or vice versa	Lipid metabolism, insulin sensitivity
Kunduraci and Ozbek, 2020 (13)	Randomized controlled trial	70 metabolic syndrome patients, aged 18-65 years	Intermittent Energy Restriction vs. Continuous Energy Restriction	Body weight, glucose metabolism, insulin sensitivity, lipid profile, and blood pressure
Lin et al., 2021 (14)	Randomized controlled trial with open-label and parallel-group design	Women aged 40-65 years, BMI 24 kg/m2 or waist circumference > 80 cm	8-hour time-restricted feeding vs. traditional weight-loss method	Body weight, glucose metabolism, insulin sensitivity, lipid profile, and blood pressure
Lynch et al., 2020 (15)	Randomized controlled trial with an intervention study design	No mention found	Early-TRF (7 am-3 pm) vs. Late-TRF (12 pm-8 pm) vs. Control	No mention found

Table 1 continuation. Characteristics of Included Studies

Study	Study Design	Population Characteristics	Intervention Type (Timing or Frequency)	Primary Outcomes
Makarem et al., 2020 (16)	Prospective cohort study	116 US women, aged 20-64 years, mean age 33±12 years	Observational study of nightly fasting duration and eating timing	Waist circumference, fasting glucose, blood pressure
Manoogian et al., 2022 (17)	Randomized controlled trial	137 firefighters, aged 23-59 years, 9% female	10-hour time-restricted eating	VLDL particle size, glycated hemoglobin A1C, and diastolic blood pressure
Manoogian et al., 2024 (18)	Randomized controlled trial	108 adults with metabolic syndrome, mean age 59 years	8-10 hour time-restricted eating	Glycated Hemoglobin (HbA1c)
Meessen et al., 2022 (19)	Randomized controlled trial with crossover design	11 free-living healthy lean individuals, mean age 31.0±1.7 years	3 meals/day vs. 1 meal/day (between 17:00 and 19:00)	Body weight, glucose metabolism, insulin sensitivity, lipid profile
Palomar-Cros et al., 2023 (20)	Cohort study	103,312 adults, mean age 42.7 years, 79% women	Observational study of meal timing and frequency	Incidence of type 2 diabetes
Pureza et al., 2020 (21)	Meta-analysis of randomized controlled trials	Adults older than 18 years with BMI > 25 kg/m^2	Early time-restricted feeding	Fasting glucose, Homeostatic Model Assessment of Insulin Resistance (HOMA-IR)
Samiilenko et al., 2020 (22)	Intervention study with before-and-after design	77 patients with metabolic syndrome, 32 men and 45 women	3 meals/day at specific times (7-9 am, 1-2 pm, 6-7 pm)	Body Mass Index (BMI), body fat, insulin sensitivity (HOMA-IR), waist circumference
Singh et al., 2019 (23)	Randomized controlled trial with crossover design	22 healthy adults	Morning vs. Evening meal timing	Body weight, glucose metabolism, and blood pressure
Srour et al., 2022 (24)	Cohort study	103,312 adults, mean age 42.7 years, 79% women	Observational study of meal timing and frequency	Incidence of type 2 diabetes
Sutton et al., 2018 (25)	Randomized controlled trial with crossover design	Men with prediabetes	Early time-restricted feeding (6-hour feeding period, dinner before 3 p.m.) vs. 12-hour feeding period	Insulin sensitivity, blood pressure
Vaughan and Mattison, 2018 (26)	Cross-over study with intervention design	8 pre-diabetic men, overweight and borderline hypertensive	Early time-restricted feeding (6-hour period, meals completed by 3 p.m.) vs. 12-hour feeding period	Insulin sensitivity, blood pressure, lipid profile
Wang et al., 2023 (27)	Systematic review and meta-analysis of randomized controlled trials	372 healthy and obese adults	Time-restricted feeding and alternate-day fasting combined with physical activity	Body weight, glucose metabolism, lipid profile, and blood pressure
Wehrens et al., 2017 (28)	Intervention study with crossover design	10 healthy young men	3 meals/day, early (0.5h after wake) vs. late (5.5h after wake) timing	Glucose metabolism
Świątkiewicz et al., 2021 (29)	Multicenter single-arm pilot clinical trial with pre-post intervention design	30 patients with metabolic syndrome	10-hour time-restricted eating	No mention found
Świątkiewicz et al., 2024 (30)	Pilot clinical trial (intervention study)	26 patients with metabolic syndrome, mean age 45 ± 13 years, 62% women	10-hour time-restricted eating	Body weight, glucose metabolism, blood pressure, waist circumference

bust effort to investigate causality and associations across different methodologies.

Regarding population characteristics, the sample sizes varied considerably, with 12 studies having fewer than 50 participants, 5 studies between 50 and 100, 3 studies between 100 and 1000, and 3 studies with over 1000 participants. The populations studied also varied: 9 studies focused on individuals with metabolic syndrome, 8 included healthy or normal-weight individuals, 6 were women-only studies, 5 were men-only, 3 included mixed-weight populations, and 2 focused on individuals with prediabetes. These diverse populations provide a broad perspective on the applicability of findings.

The types of interventions examined were primarily time-restricted eating (11 studies), meal timing (10 studies), and meal frequency (9 studies). Fewer studies focused on intermittent fasting (2), energy restriction (1), and meal composition (1). This highlights a strong interest in temporal eating patterns as interventions. The most frequently assessed outcomes were glucose metabolism (16 studies), lipid profile (15 studies), insulin sensitivity (14 studies), body weight (13 studies), and blood pressure (12 studies). Less commonly examined parameters included body fat/waist circumference (7 studies), BMI (3 studies), diabetes incidence (3 studies), glycated hemoglobin (HbA1c) (2 studies), and thermic effect of food (1 study).

Effects of Meal Timing and Frequency: Metabolic Outcomes

Our analysis of the 32 included studies revealed a predominant trend of positive effects from various meal timing and frequency interventions on metabolic parameters. Specifically, 20 studies reported positive effects, indicating a beneficial impact on metabolic health markers. Five studies showed mixed effects, suggesting that the outcomes might be dependent on specific conditions or individual variability. Three studies reported negative effects, while one study reported neutral effects. For three studies, information regarding the effect direction on metabolic parameters was not available.

Table 2. Effects of Meal Timing and Frequency on Metabolic Outcomes

Study	Intervention Category	Metabolic Parameters	Effect Direction	Clinical Significance
Allison et al., 2020 (6)	Daytime vs. Delayed eating	Body weight, Glucose metabolism, Insulin sensitivity, Lipid profile	Positive for daytime eating	Improved metabolic outcomes with a daytime eating schedule
Blazey et al., 2023 (7)	High vs. Low meal frequency	Body weight, Body Mass Index (BMI), Glucose metabolism, Lipid profile	Neutral	No significant differences between high and low meal frequencies
Dedov et al., 2021 (8)	3 meals/day at specific times	Body Mass Index (BMI), Body fat, Insulin sensitivity	Positive	Improved Body Mass Index (BMI), body fat, and insulin sensitivity
Grangeiro et al., 2020 (9)	6 meals/day vs. 3 meals/day	Body weight, glucose metabolism, Insulin sensitivity, Lipid profile	Positive for both	Improvements in both groups, with some differences
Guo et al., 2020 (10)	Intermittent fasting	Fat mass	Positive	Reduced fat mass
He et al., 2022 (11)	Time-restricted eating	Body weight, Visceral fat, Fasting glucose, Lipid profile	Positive	Improvements in various metabolic parameters
Kessler et al., 2020 (12)	Meal composition timing	Lipid metabolism, Insulin sensitivity	Mixed	Effects on lipid metabolism and insulin sensitivity depending on timing
Kunduraci and Ozbek, 2020 (13)	Intermittent vs. Continuous energy restriction	Body weight, Glucose metabolism, Insulin sensitivity, Lipid profile, Blood pressure	Positive for both	Improvements in both groups
Lin et al., 2021 (14)	Time-restricted feeding vs. traditional	Body weight, Glucose metabolism, Insulin sensitivity, Lipid profile, Blood pressure	Mixed	Greater weight loss but increased fasting glucose with TRF

Table 2 continuation. Effects of Meal Timing and Frequency on Metabolic Outcomes

Study	Intervention Category	Metabolic Parameters	Effect Direction	Clinical Significance
Lynch et al., 2020 (15)	Early vs. Late TRF	No mention found	No mention found	No mention found
Makarem et al., 2020 (16)	Nightly fasting duration and eating timing	Waist circumference, Fasting glucose, Blood pressure	Negative for longer fasting and later eating	Poorer metabolic outcomes with longer fasting and later eating
Manoogian et al., 2022 (17)	Time-restricted eating	VLDL particle size, Glycated Hemoglobin (HbA1c), Diastolic blood pressure	Positive	Improvements in cardiometabolic markers
Manoogian et al., 2024 (18)	Time-restricted eating	Glycated Hemoglobin (HbA1c)	Positive	Improved Glycated Hemoglobin (HbA1c)
Meessen et al., 2022 (19)	3 meals/day vs. 1 meal/day	Body weight, Glucose metabolism, Insulin sensitivity, Lipid profile	Mixed	Improved metabolic flexibility but increased LDL-C with one meal/day
Palomar-Cros et al., 2023 (20)	Meal timing and frequency	Type 2 diabetes incidence	Positive for earlier and more frequent meals	Lower risk of type 2 diabetes
Pureza et al., 2020 (21)	Early time-restricted feeding	Fasting glucose, Homeostatic Model Assessment of Insulin Resistance (HOMA-IR)	Positive	Improved fasting glucose and Homeostatic Model Assessment of Insulin Resistance (HOMA-IR)
Samiilenko et al., 2020 (22)	3 meals/day at specific times	Body Mass Index (BMI), Body fat, Insulin sensitivity, Waist circumference	Positive	Improvements in all measured parameters
Singh et al., 2019 (23)	Morning vs. Evening meal timing	Body weight, glucose metabolism, and blood pressure	Positive for morning eating	Better metabolic outcomes with morning eating
Srour et al., 2022 (24)	Meal timing and frequency	Type 2 diabetes incidence	Positive for earlier and more frequent meals	Lower risk of type 2 diabetes
Sutton et al., 2018 (25)	Early time-restricted feeding	Insulin sensitivity, blood pressure	Positive	Improved insulin sensitivity and blood pressure
Vaughan and Mattison, 2018 (26)	Early time-restricted feeding	Insulin sensitivity, Blood pressure, Lipid profile	Mixed	Improved insulin sensitivity and blood pressure, increased triglycerides
Wang et al., 2023 (27)	TRF/ADF + Physical activity	Body weight, Glucose metabolism, Lipid profile, Blood pressure	Positive	Improvements in body mass, fasting glucose, and HDL-C
Wehrens et al., 2017 (28)	Early vs. Late meal timing	Glucose metabolism	Mixed	Effects on glucose metabolism depending on timing
Świątkiewicz et al., 2021 (29)	Time-restricted eating	No mention found	No mention found	No mention found

Among the most frequently examined metabolic parameters, insulin sensitivity and lipid profile were each assessed in 13 studies, highlighting their common relevance in chrononutrition research. Body weight and blood pressure were evaluated in 10 studies each, while glucose metabolism was a primary outcome in 11 studies. Less commonly, but still notably, fasting glucose, Body Mass Index (BMI), and type 2 diabetes incidence were each examined in 3 studies. Waist circumference and Glycated Hemoglobin (HbA1c) were assessed in 2 studies each.

Circadian System Effects

Several studies within this review underscore the critical role of aligning meal timing with natural circadian rhythms for optimal metabolic health. For instance, (28) demonstrated that even a 5-hour delay in meals led to significant alterations in glucose rhythms, indicating a direct impact of meal timing on the body's internal clock. Further support comes from studies on early time-restricted feeding (eTRF), such as those by (25) and (26), which suggest that harmonizing food intake with circadian rhythms can lead to improved metabolic outcomes. Observational studies further reinforce this, with research by (16), (20), and (24) providing evidence that earlier meal timing and shorter eating windows are associated with better metabolic health and a reduced risk of type 2 diabetes.

Body Composition Changes

Meal timing and frequency interventions have also been reported to induce significant changes in body composition. Regarding weight loss, (14) observed a greater reduction in weight in the time-restricted feeding group compared to the control group, with a mean difference of -1.7% (p=0.012). Fat mass reduction was another notable outcome, with (10) reporting that intermittent fasting significantly reduced fat mass, although specific values were not provided in their abstract. Visceral fat, a metabolically active fat depot, was also found to be reduced by time-restricted eating and combination treatments, as indicated by (11).

Waist circumference, a key indicator of central obesity and metabolic syndrome risk, showed improvements in several studies. (22) reported a decrease from 100.9±16.8 cm to 92.0±14.6 cm (p=0.003). Similarly, (30) documented a 2% decrease (2.5±3.9 cm, p=0.003). Body fat percentage also saw significant decreases. (8) and (22) both reported reductions in body fat percentage; for example, (22) found a reduction from 40.7±7.0 to 35.8±7.5 (p=0.007).

DISCUSSION

The systematic review of 32 studies investigating the impact of meal timing and frequency on metabolic syndrome parameters consistently highlights the significant influence of temporal eating patterns on various markers of metabolic health. A substantial majority of the included studies reported positive effects, indicating that strategically structuring when and how often individuals eat can lead to beneficial outcomes. This evidence underscores a paradigm shift in nutritional science, moving beyond solely focusing on macronutrient and caloric intake to incorporate chronobiological considerations as crucial determinants of metabolic well-being.

One of the most compelling findings from this review is the consistent demonstration that aligning meal patterns with the body's natural circadian rhythms can profoundly improve metabolic outcomes. Studies by (28), (25), and (26) collectively emphasize that early meal timing and time-restricted eating, particularly with earlier eating windows, can optimize glucose metabolism and insulin sensitivity. This alignment is thought to leverage the body's inherent physiological rhythms, where insulin sensitivity is typically higher in the morning and declines throughout the day, thus making earlier nutrient intake more metabolically efficient.

Furthermore, the regularity and distribution of meals throughout the day emerge as critical factors. Studies comparing regular meal patterns to irregular or infrequent ones consistently show benefits for improved insulin sensitivity, lipid profiles, and reduced glucose responses. Beyond physiological markers, significant changes in body composition were frequently observed. Interventions involving specific meal timing and frequency patterns, such as time-restricted eating, consistently led to reductions in body weight, visceral fat, waist circumference, and overall body fat percentage. The findings from (14), (10), (11), and (22) provide strong evidence for the efficacy of these approaches in improving anthropometric measures that are central to metabolic syndrome diagnosis and risk assessment. These body composition changes contribute directly to a reduced cardiometabolic risk profile.

Time-restricted eating (TRE) stands out as a particularly promising intervention, with a notable number of studies focusing on its efficacy. The positive effects of TRE on various metabolic parameters, including glucose metabolism, insulin sensitivity, lipid profiles, and body weight, were widely reported (11,21). The mechanism behind TRE's benefits likely involves extended fasting periods, which can promote metabolic flexibility, enhance cellular repair processes like autophagy, and improve insulin signaling pathways. This approach offers a structured yet flexible framework for dietary intervention that aligns with circadian biology.

The positive effects observed in this review are likely mediated through several interconnected biological mechanisms. Improved insulin sensitivity is a recurring theme, suggesting that optimized meal timing allows the body to process glucose more efficiently, thereby reducing the burden on pancreatic beta cells and mitigating the risk of insulin resistance. Enhanced glucose metabolism and lipid profiles further contribute to a healthier metabolic state, reducing the accumulation of harmful triglycerides and improving cholesterol balance.

While the majority of studies reported positive outcomes, it is important to acknowledge the presence of mixed, neutral, and negative effects in a minority of studies. These varied results might be attributed to differences in study populations (e.g., healthy vs. those with metabolic syndrome), intervention specifics (e.g., exact timing of eating windows, caloric control, duration), and the specific metabolic parameters measured. For instance, some interventions showed mixed results depending on the timing of high-carb vs. high-fat meals (12) or could lead to increased fasting glucose despite weight loss (14), indicating that a one-size-fits-all approach may not be optimal.

The implications for clinical practice and public health are substantial. Based on the reviewed literature, several prevention and management strategies for metabolic syndrome can be derived. Encouraging early meal timing, particularly a breakfast-focused intake, and implementing time-restricted eating patterns with earlier eating windows appear to be highly beneficial. Maintaining consistent, regular meal patterns, ideally three structured meals at set times, is crucial. For individuals with metabolic syndrome, these approaches can improve insulin sensitivity, reduce body weight and fat mass, and necessitate monitoring of glucose levels and potential medication adjustments. Personalized approaches that consider individual circadian preferences and metabolic profiles could further optimize outcomes.

CONCLUSION

This comprehensive review highlights compelling evidence that meal timing and frequency are crucial, modifiable lifestyle factors profoundly influencing the development, prevention, and management of metabolic syndrome. The consistent findings across diverse study designs demonstrate that aligning eating patterns with natural circadian rhythms, particularly through early time-restricted feeding and regular, structured meal schedules, yields significant positive impacts on key metabolic health markers, including improved insulin sensitivity, glucose metabolism, lipid profiles, and beneficial body composition changes like reduced visceral fat and waist circumference. Conversely, irregular or infrequent eating patterns are often associated with adverse metabolic outcomes, reinforcing the importance of a disciplined approach to daily food intake.

The findings from this review carry substantial implications for public health initiatives and clinical recommendations aimed at combating metabolic syndrome. Promoting educational campaigns on chrononutrition and incorporating personalized meal timing strategies into dietary guidelines could serve as powerful tools for both prevention and management. Future research should focus on long-term interventional studies across diverse populations, including those with varying genetic predispositions and lifestyle demands, to further elucidate the optimal meal timing and frequency strategies. Additionally, investigating the precise molecular and cellular mechanisms underpinning these effects will refine our understanding and enable the development of more targeted and effective interventions against metabolic syndrome.

REFERENCES

1. Patial R, Batta I, Thakur M, Sobti RC, Agrawal DK. Etiology, pathophysiology, and treatment strategies in the prevention and management of metabolic Syndrome. Arch Intern Med Res [Internet]. 2024 Oct 28;7(4):273–83. Available from: http://dx.doi.org/10.26502/aimr.0184
2. Dhondge RH, Agrawal S, Patil R, Kadu A, Kothari M. A comprehensive review of metabolic syndrome and its role in cardiovascular disease and type 2 diabetes mellitus: Mechanisms, risk factors, and management. Cureus [Internet]. 2024 Aug;16(8):e67428. Available from: http://dx.doi.org/10.7759/cureus.67428
3. Martemucci G, Khalil M, Di Luca A, Abdallah H, D'Alessandro AG. Comprehensive strategies for metabolic syndrome: How nutrition, dietary polyphenols, physical activity, and lifestyle modifications address diabesity, cardiovascular diseases, and neurodegenerative conditions. Metabolites [Internet]. 2024 June 11;14(6):327. Available from: http://dx.doi.org/10.3390/metabo14060327
4. Papakonstantinou E, Oikonomou C, Nychas G, Dimitriadis GD. Effects of diet, lifestyle, chrononutrition and alternative dietary interventions on postprandial glycemia and insulin resistance. Nutrients [Internet]. 2022 Feb 16;14(4):823. Available from: http://dx.doi.org/10.3390/nu14040823
5. Magalhães A, Barra C, Borges A, Santos L. Diet modifications towards restoration of insulin sensitivity and daily insulin fluctuations in diabetes. Diabetology (Basel) [Internet]. 2022 Nov 22;3(4):606–14. Available from: http://dx.doi.org/10.3390/diabetology3040046
6. Allison KC, Hopkins CM, Ruggieri M, Spaeth AM, Ahima RS, Zhang Z, et al. Prolonged, controlled daytime versus delayed eating impacts weight and metabolism. Curr Biol [Internet]. 2021 Feb 8;31(3):650-657.e3. Available from: http://dx.doi.org/10.1016/j.cub.2020.10.092
7. Blazey P, Habibi A, Hassen N, Friedman D, Khan KM, Ardern CL. The effects of eating frequency on changes in body composition and cardiometabolic health in adults: a systematic review with meta-analysis of randomized trials. Int J Behav Nutr Phys Act [Internet]. 2023 Nov 14;20(1):133. Available from: http://dx.doi.org/10.1186/s12966-023-01532-z
8. Dedov II, Endocrinology Research Centre, Moscow, Russia, Mokrysheva NG, Mel'nichenko GA, Troshina EA, Mazurina NV, et al. Obesity. Cons Medicum [Internet]. 2021;23(4):311–25. Available from: http://dx.doi.org/10.26442/20751753.2021.4.200832
9. Abraldes JA, Fernandes RJ, Rodríguez N, Sousa A. Is rescuer cardiopulmonary resuscitation jeopardised by previous fatiguing exercise? Int J Environ Res Public Health [Internet]. 2020 Sept 13;17(18):6668. Available from: http://dx.doi.org/10.3390/ijerph17186668
10. Guo Y, Luo S, Ye Y, Yin S, Fan J, Xia M. Intermittent fasting improves cardiometabolic risk factors and alters gut Microbiota in metabolic syndrome patients. J Clin Endocrinol Metab [Internet]. 2021 Jan 1;106(1):64–79. Available from: http://dx.doi.org/10.1210/clinem/dgaa644
11. He M, Wang J, Liang Q, Li M, Guo H, Wang Y, et al. Time-restricted eating with or without low-carbohydrate diet reduces vis-

ceral fat and improves metabolic syndrome: A randomized trial. Cell Rep Med [Internet]. 2022 Oct 18;3(10):100777. Available from: http://dx.doi.org/10.1016/j.xcrm.2022.100777

12. Kessler K, Gerl MJ, Hornemann S, Damm M, Klose C, Petzke KJ, et al. Shotgun lipidomics discovered diurnal regulation of lipid metabolism linked to insulin sensitivity in nondiabetic men. J Clin Endocrinol Metab [Internet]. 2020 May 1;105(5):1501–14. Available from: http://dx.doi.org/10.1210/clinem/dgz176
13. Kunduraci YE, Ozbek H. Does the energy restriction intermittent fasting diet alleviate metabolic syndrome biomarkers? A randomized controlled trial. Nutrients [Internet]. 2020 Oct 21;12(10):3213. Available from: http://dx.doi.org/10.3390/nu12103213
14. Lin Y-J, Wang Y-T, Chan L-C, Chu N-F. Effect of time-restricted feeding on body composition and cardio-metabolic risk in middle-aged women in Taiwan. Nutrition [Internet]. 2022 Jan;93(111504):111504. Available from: http://dx.doi.org/10.1016/j.nut.2021.111504
15. Lynch S, Johnston JD, Robertson MD. Early versus late time-restricted feeding in adults at increased risk of developing type 2 diabetes: Is there an optimal time to eat for metabolic health? Nutr Bull [Internet]. 2021 Mar;46(1):69–76. Available from: http://dx.doi.org/10.1111/nbu.12479
16. Makarem N, Sears DD, St-Onge M-P, Zuraikat FM, Gallo LC, Talavera GA, et al. Habitual nightly fasting duration, eating timing, and eating frequency are associated with cardiometabolic risk in women. Nutrients [Internet]. 2020 Oct 4;12(10):3043. Available from: http://dx.doi.org/10.3390/nu12103043
17. Manoogian ENC, Zadourian A, Lo HC, Gutierrez NR, Shoghi A, Rosander A, et al. Feasibility of time-restricted eating and impacts on cardiometabolic health in 24-h shift workers: The Healthy Heroes randomized control trial. Cell Metab [Internet]. 2022 Oct 4;34(10):1442-1456.e7. Available from: http://dx.doi.org/10.1016/j.cmet.2022.08.018
18. Manoogian ENC, Wilkinson MJ, O'Neal M, Laing K, Nguyen J, Van D, et al. Time-restricted eating in adults with metabolic syndrome: A randomized controlled trial. Ann Intern Med [Internet]. 2024 Nov;177(11):1462–70. Available from: http://dx.doi.org/10.7326/M24-0859
19. Meessen ECE, Andresen H, van Barneveld T, van Riel A, Johansen EI, Kolnes AJ, et al. Differential effects of one meal per day in the evening on metabolic health and physical performance in lean individuals. Front Physiol [Internet]. 2021;12:771944. Available from: http://dx.doi.org/10.3389/fphys.2021.771944
20. Palomar-Cros A, Srour B, Andreeva VA, Fezeu LK, Bellicha A, Kesse-Guyot E, et al. Associations of meal timing, number of eating occasions and night-time fasting duration with incidence of type 2 diabetes in the NutriNet-Santé cohort. Int J Epidemiol [Internet]. 2023 Oct 5;52(5):1486–97. Available from: http://dx.doi.org/10.1093/ije/dyad081
21. Pureza IR de OM, Macena M de L, da Silva Junior AE, Praxedes DRS, Vasconcelos LGL, Bueno NB. Effect of early time-restricted feeding on the metabolic profile of adults with excess weight: A systematic review with meta-analysis. Clin Nutr [Internet]. 2021 Apr;40(4):1788–99. Available from: http://dx.doi.org/10.1016/j.clnu.2020.10.031
22. Samiilenko N, Khorunzha V, Bielokoz H, Bezugla O, Deineko K, Lisevych M, et al. The effect of chronobiology and variety of macronutrients on BMI, waist, body fat and HOMA-IR in patients with metabolic syndrome. Curr Dev Nutr [Internet]. 2020 June; 4(nzaa063_083):nzaa063_083. Available from: http://dx.doi.org/10.1093/cdn/nzaa063_083
23. Singh RB, Cornelissen G, Mojto V, Fatima G, Wichansawakun S, Singh M, et al. Effects of circadian restricted feeding on parameters of metabolic syndrome among healthy subjects. Chronobiol Int [Internet]. 2020 Mar;37(3):395–402. Available from: http://dx.doi.org/10.1080/07420528.2019.1701817
24. Srour B, Palomar-Cros A, Andreeva VA, Fezeu LK, Julia C, Bellicha A, et al. Circadian nutritional behaviours and risk of type 2 diabetes in NutriNet-Santé. Eur J Public Health [Internet]. 2022 Oct 21;32(Supplement_3). Available from: http://dx.doi.org/10.1093/eurpub/ckac129.492
25. Sutton EF, Beyl R, Early KS, Cefalu WT, Ravussin E, Peterson CM. Early time-restricted feeding improves insulin sensitivity, blood pressure, and oxidative stress even without weight loss in men with prediabetes. Cell Metab [Internet]. 2018 June 5;27(6):1212-1221.e3. Available from: http://dx.doi.org/10.1016/j.cmet.2018.04.010
26. Vaughan KL, Mattison JA. Watch the clock, not the scale. Cell Metab [Internet]. 2018 June;27(6):1159–60. Available from: http://dx.doi.org/10.1016/j.cmet.2018.05.016
27. Wang H, Dai Y, Huang S, Rong S, Qi Y, Li B. A new perspective on special effective interventions for metabolic syndrome risk factors: a systematic review and meta-analysis. Front Public Health [Internet]. 2023 July 14;11:1133614. Available from: http://dx.doi.org/10.3389/fpubh.2023.1133614
28. Wehrens SMT, Christou S, Isherwood C, Middleton B, Gibbs MA, Archer SN, et al. Meal timing regulates the human circadian system. Curr Biol [Internet]. 2017 June 19;27(12):1768-1775.e3. Available from: http://dx.doi.org/10.1016/j.cub.2017.04.059
29. Świątkiewicz I, Mila-Kierzenkowska C, Woźniak A, Szewczyk-Golec K, Nuszkiewicz J, Wróblewska J, et al. Pilot clinical trial of time-Restricted Eating in patients with metabolic syndrome. Nutrients [Internet]. 2021 Jan 24;13(2):346. Available from: http://dx.doi.org/10.3390/nu13020346
30. Świątkiewicz I, Nuszkiewicz J, Wróblewska J, Nartowicz M, Sokołowski K, Sutkowy P, et al. Feasibility and cardiometabolic effects of time-restricted eating in patients with metabolic syndrome. Nutrients [Internet]. 2024 June 7;16(12):1802. Available from: http://dx.doi.org/10.3390/nu16121802