RJNMSR
Review Journal of Neurological & Medical Sciences Review

Volume 3, Issue 8, 2025

CHRONONUTRITION AND CIRCADIAN RHYTHMICITY: EXPLORING THE TEMPORAL DYNAMICS OF NUTRIENT INTAKE IN THE REGULATION OF GLUCOSE HOMEOSTASIS AND THE THERAPEUTIC MANAGEMENT OF TYPE 2 DIABETES MELLITUS

Saba Shahzadi[1], Khadija Zain Sani[2], Muhammad Hassan Shabbir[1], Muhammad Ahmad Afzal[*3], Eman Mukhtar[4], Shazia Ashraf[5], Bareera Mahmood[6], Muhammad Naeem Zafar[7], Shiza Gull[8], Sarah Sher Khan[9], Muhammad Usman Rasheed[10]

[1]National Institute of Food Science and Technology, University of Agriculture Faisalabad, Pakistan,
[2]Department of Nutrition, Clinical Dietitian Smart Institute of Rehabilitation Medicine, Islamabad, Pakistan,
*[*3]Department of Human Nutrition and Dietetics, Faculty of Medical Sciences, Government College University Faisalabad, Pakistan*
[4]Clinical Nutrition Department, Sunaan Hospital kotla, Gujrat, Pakistan.
[5]NUR International University, Lahore, Pakistan,
[6]Department of Human Nutrition and Dietetics, Faculty of Rehabilitation and Allied Health Sciences, Riphah International University, Faisalabad, Pakistan
[7]School of Allied Health Sciences, Lahore General Hospital, Lahore, Pakistan
[8]Institute of Home Sciences, Faculty of Food, Nutrition and Home Sciences, University of Agriculture Faisalabad, Pakistan
[9]Faculty of Eastern Medicine, Hamdard University Islamabad Campus, Pakistan
[10]Department of Chemistry, Faculty of Sciences, University of Agriculture Faisalabad, Pakistan

[1]sabasattar323@gmail.com/hassanmuhammad481@gmail.com,[2]dnkhadijazainsani@gmail.com,
[*3]ahmadansarians17@gmail.com,[4]emanmukhtar3164@gmail.com,[5]shazia.zahra@gmail.com,
[6]bareeramahmood05@gmail.com,[7]naeemzafarkasuri@gmail.com,[8]shizagul249@gmail.com,
[9]sarahsherkhan15@gmail.com, [10]usman.rasheed463@gmail.com

Corresponding Author: *
Muhammad Ahmad Afzal
DOI: https://doi.org/10.5281/zenodo.17984112

Received	Accepted	Published
19 October 2025	30 November 2025	19 December 2025

ABSTRACT

Circadian rhythms are 24-hour cycles, which are controlled by internal molecular oscillators collectively known as the circadian clock. Nutritional factors on circadian rhythmicity are associated with a correlation of the timing of eating the food and the food content, which is referred to as chrononutrition. These aspects are regulated by personal chronotype attributes, in that evening or late chronotype individuals have a biological tendency to eat late in the day. Empirical evidence reveals that the effect of the time of day on the postprandial (PP) glucose response is enormous, and thus the time of day has a significant influence on the pathophysiology of type 2 diabetes (T2D). Both cross-sectional and experimental studies have shown that eating in the morning and not in the evening is beneficial in terms of PP glycaemia. The addition of protein and fat in the macronutrient content of night meals has been an easy approach to mitigate PP glycaemic excursion. Foods with low glycaemic index taken in the morning has been found to give a better response in terms of glycaemic response compared to those taken at night. The combination of fats and proteins with carbohydrate sources like bread and rice has also been demonstrated to lower glycaemic response. Moreover, the order of food service has a significant potential in lowering the PP blood glucose, as vegetables should be eaten at the start, then meat, and finally rice. These empirical suggestions can

thus be considered measures to improve glycaemic control as opposed to merely measuring the nutritional content of individual meals, and they may play a role in the optimisation of dietary patterns in patients with diabetes. More clarification of this intriguing field of study is necessary to gain more knowledge about the circadian system and its nutritional implications that can eventually reduce the burden of T2D.
Keywords: *CHRONOTYPE, POSTPRANDIAL GLUCOSE, GLYCAEMIA, INSULIN, MEAL TIMING*

INTRODUCTION

Type 2 diabetes mellitus (T2DM) is a chronic metabolic condition that is marked by sustained hyperglycaemic conditions that occur as a result of cell insensitivity to insulin. This condition is characterized by the inability of the body to properly use insulin, resulting in chronically high blood glucose levels (Afzal et al., 2025). The evidence concerning diabetes prevalence in the world has increased significantly; the current projections state that there are 537,000 adults with the disease in 2021, and it is expected that the number will rise to 783,000 adults by 2045. This pattern highlights a significant and increasing public health load worldwide (Forouhi & Wareham, 2022). It is also noted that the average annual total cost of a patient or a household fighting with diabetes in low- and middle-income countries is about 1017.05 USD (Ashraf et al., 2025). Type 2 diabetes (T2D) can be prevented or its onset can be delayed, by maintaining a normal body weight, avoiding tobacco use, eating a healthy diet, and engaging in regular physical activity. Diet, exercise, medication, and routine screening and treatment for complications can all help prevent or postpone the consequences of diabetes (WHO, 2024).

Circadian rhythms are the 24-hour cycles that regulate the sleep-wake chain in the organism and a variety of other endogenous biological activities, all coordinated by molecular oscillators that are collectively known as the circadian clock. The body is primed for events that occur during the day by its circadian clock. It regulates a set of physiological parameters, such as hormone secretions, cardiac rhythm, kidney perfusion, the sleep-wake cycle itself, and core body temperature changes (Begemann et al., 2025). The circadian clock is localized in the suprachiasmatic nuclei (SCN), and it is the main regulator of the peripheral clock system. In the case of disruption or ablation of the SCN, circadian rhythms that regulate the sleep cycle and the release of various endocrine factors are significantly reduced. The SCN contains discrete groups of peptide-bearing neurons that are essential in the entrainment and phase shifting of circadian rhythms, of which the somatostatinergic, vasoactive intestinal peptide (VIP), and arginine vasopressin (AVP) neuron subgroups are the most important (Ono et al., 2024). Circadian rhythmicity is essential in regulating the metabolic processes since it controls the expression and/or activity of enzymes that mediate glucose metabolism (Lloyd et al., 2025). Over the last few years, there has been an accumulating amount of evidence that suggests that the circadian clock system can be engaged to communicate with nutrients and can affect physiological processes. This new field of work, known as chrononutrition, highlights the bidirectional nature of the circadian rhythms and metabolism (Franzago et al., 2023).

In modern society, shift work predominates, and the level of insomnia is very high, which interferes with adherence to endogenous circadian timing (Oros et al., 2025). It has been demonstrated that misalignment of the circadian clock changes food intake, glucose metabolism, and weight regulation, and causes obesity (Chaput et al., 2023).

This review article focuses on diabetes and its relation with meal patterns and timings, and how the intake of nutrients can affect glycaemic control by focusing on recent studies concerning human or animal models.

Biological Clock Regulation of Glucose Metabolism

The body's tolerance to glucose fluctuates within a 24-hour period, confirming the fact that the human body follows a circadian rhythm. Glucose tolerance often reaches its zenith during daylight hours, coinciding with regular food intake, and diminishes during nocturnal hours, when fasting is prevalent (Díaz-Rizzolo et al., 2024). The SCN of the hypothalamus contains the central pacemaker of the circadian clock, which coordinates peripheral oscillators in the body by means of neural and endocrine pathways, and is largely preoccupied with the rhythmical secretion of cortisol (Van Drunen & Eckel-Mahan, 2021; Bautista et al., 2025). Hormones such as cortisol and insulin govern glucose metabolism and also exhibit circadian oscillation (Koop & Oster, 2022). The retinal ganglion cells detect light and transmit it into the SCN via the retinohypothalamic tract (RHT). Melanopsin, glutamate, and pituitary adenylate cyclase-activating polypeptide (PACAP) are the main neurotransmitters in this. The SCN then coordinates circadian rhythm in other bodily systems like the liver, adipose tissue, gastrointestinal tract, and skeletal muscle. Food also acts as a zeitgeber; for example, glucose from carbohydrates affects liver rhythms and glucose tolerance, causing it to be higher in the morning and lower at night. Dietary fibre helps the gut microbiota and keeps the intestinal clocks in sync. On the other hand, too much dietary fat can mess up the rhythmic function of the liver and fat tissue, as depicted in Figure 1.

It was observed that circadian rhythm disruption by ambient light throughout the lifespan triggers metabolic dysfunction in adult mice. As noted by Her et al. (2024), circadian rhythm disruption contributes to the increasing incidence of glucose intolerance and enhances insulin resistance in female mice. The study also showed that both male and female mice become prone to obesogenic problems and develop metabolic dysfunctions when the disruption of the circadian system is combined with a high-fat diet. All these observations indicate that environmental disruption of circadian rhythms during the lifespan enhances the likelihood of obesity and T2D in adulthood, indicating that circadian control plays an important role in the regulation of insulin secretion and sensitivity with a significant impact on glucose metabolism. The disruption of meal timing has been associated with the development of glucose intolerance, allegedly caused by the increase in the discrepancy between the central circadian pacemaker and peripheral oscillatory processes working in the hepatic and pancreatic populations of cells (Hu et al., 2025). The dietary pattern-based effects on circadian rhythmicity are clearly mediated by the complex interaction of variables, such as meal timing and nutrient content, that have the potential to cause circadian disruption and, consequently, to regulate the onset of metabolic disorders, such as T2D, obesity, non-alcoholic fatty liver disease (NAFLD), cirrhosis, and hepatocellular carcinoma (Zhao et al., 2022). Although temperature and social interactions are of minor importance, the timing of meals is an important determinant of circadian alignment. There are also internal factors, including genetics, hormones, and age, that influence circadian regulation and hormonal rhythms, such as cortisol and melatonin, which interact synergistically with the timing of food intake. Circadian rhythms diminish with age; however, dietary measures, including regular meal schedules and eating more fibre, can be used to restore them. In general, food serves as the key intervener in the interaction between the environment and the internal physiology, balancing central and peripheral clocks (BaHammam & Pirzada, 2023; Reytor-González et al., 2025).

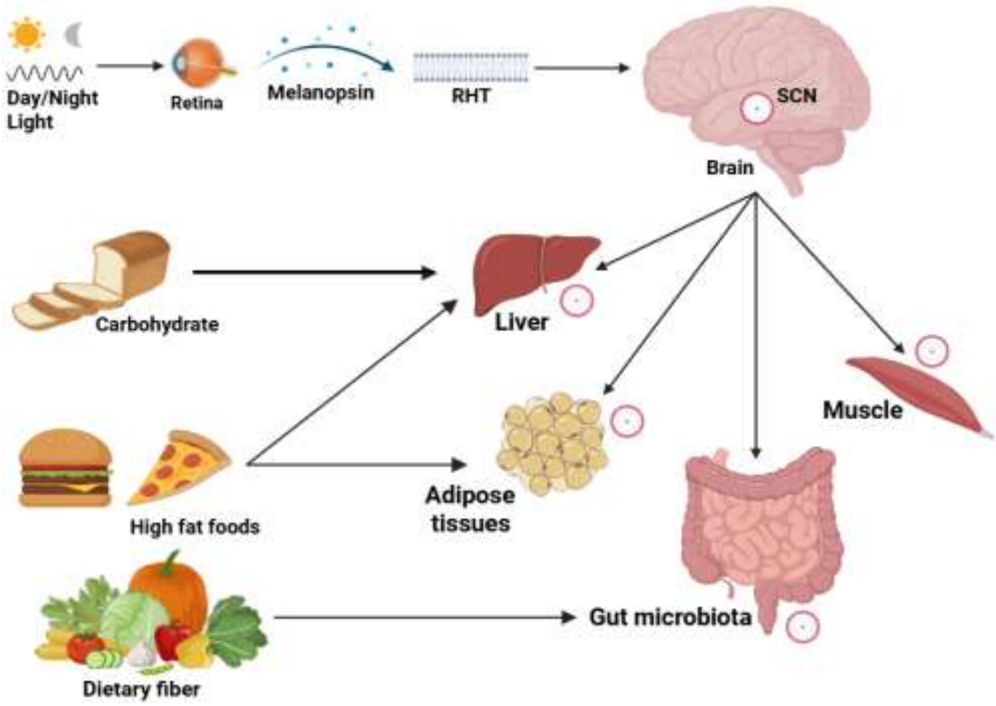

Figure 1. Comparative analysis of light- and food-mediated circadian pathways

Impact of Meal Frequency and Timing on Glucose Homeostasis

The current lifestyles have affected eating habits, and this can be attributed to shift work, late-night eating, artificial lights, and irregular sleep timing, which have brought about an imbalance between the body clock and the meal schedule. Such asynchronization compromises the process of glucose metabolism and leads to imbalances in metabolism, such as glucose intolerance (Dobrovinskaya et al., 2024). Humans are diurnal species; therefore, this disruption in the synchrony between the light-dark cycle and the food intake increases the propensity to sleep disturbances in night shift workers. Endocrine disorders have also been attributed to shift work. Shift work was observed to increase the risk of developing diabetes mellitus in an observational study. Furthermore, inadequate sleep, which is commonly observed in shift workers, was found to be associated with higher plasma glucose levels and increased insulin release rates (Lee, 2022). Various studies also suggested that shift employees have a higher body mass index (BMI) and prevalence of developing obesity as compared to daytime workers (Tosoratto et al., 2024). Research conducted by Tosoratto et al. (2025) also shows that the occurrence of shift work has been positively associated with adverse metabolic conditions, especially the phenomenon of insulin resistance, which is one of the main factors that predispose the development of cardiometabolic diseases.

There are emerging signs that chrononutrition is influenced by a person's chronotype. A chronotype refers to the tendency of the human body to prefer certain times of day for sleep or wakefulness, which is controlled by endogenous circadian rhythms and is influenced by genetic factors. This typology is known to forecast differences in whether a person will be a morningness (early bird) or eveningness (night owl), consequently, determining energy levels, productivity, and other daily processes throughout the 24-hour cycle (Chauhan et al., 2023). Persons of an evening chronotype are those with a biological predisposition to eat later in the day, which is linked to high-energy consumption in the form of unhealthy snacks and poor distribution of overall daily energy intake. This late meal habit is linked to a series of negative health effects, which are explained by the reduced metabolic effectiveness of the biological body in handling the food during the night-time (van der Merwe et al., 2022).

A number of articles have reported a strong association between skipping breakfast and the onset of insulin resistance or T2D (Afzal et al., 2025). People who skipped breakfast are at greater risk of developing T2D, along with other complications, as compared to people who consumed breakfast, with ratios fluctuating across different populations. The Bath Breakfast Project, which follows a six-week intervention, also concluded that the BMI remained unaltered in both the breakfast-consuming and breakfast-skipping groups in lean and obese individuals. Breakfast was also noted to balance the blood sugar levels of later meals, and that chronic morning fasting lowers glucose tolerance (Afzal et al., 2025). Solangi et al. (2025) also noted significantly higher concentrations of total cholesterol (TC), triglycerides (TG), low-density lipoprotein cholesterol (LDL-C), very low-density lipoprotein cholesterol (VLDL-C), and total lipids (TL) in the breakfast skippers as compared to breakfast non-skippers. Eveningness has been observed to be linked to skipping breakfast, eating at later hours, and nocturnal food consumption, which tends to lead to low sleep quality. This can be explained by the lack of enough time to be spent on eating during the day, or the lack of morning appetite (Bazzani et al., 2022). Afzal et al. (2025) also highlighted that healthy participants who did not eat breakfast and ate large meals at lunch and dinner, because of compensatory eating in the later meals, had higher postprandial (PP) glucose levels, especially after dinner. Skipping breakfast, which is further aggravated by eating meals during the night, can postpone circadian rhythms. People who skip breakfast do so because appetite signalling is blunted by the disruption of biological clocks. Misplacing the circadian clock by feeding at the wrong time worsens the glycaemic control and increases the chances of T2D (Kim et al., 2025).

It has been shown that morning and evening meal consumption has different implications on glucose metabolism in human beings. Interestingly, the rise in the glucose level of the blood was observable in the aftermath of the late evening meal, but the highest level was attained later in the night and during sleep. The evening meals, therefore, can trigger PP hyperglycaemia, and this reflects a loss of glucose tolerance from morning to night (Byun et al., 2020). A cross-sectional study conducted by Shimizu et al. (2025) reported that irregular meal timing is proved to be strongly related to poor glycaemic control in women with type 1 diabetes mellitus (T1DM) and highly associated with a higher prevalence of obesity in men with T2DM. Moreover, late dinner intake has been linked with a high haemoglobin A1c (HbA1c) level and high BMI among patients with T2DM.

In some acute experimental studies, healthy people and people with T2DM had greater levels of blood glucose and insulin after nocturnal meals, hence signifying an augmented physiologic reaction to late evening caloric consumption. These studies conclude that circadian rhythm perturbation can play a role in the enhancement of a natural nocturnal decrease in glucose tolerance (Chauhan et al., 2024). An interesting point was also noted by researchers that people with diabetes have an inverted circadian rhythm, meaning that their glycemia and insulin sensitivity are generally better in the evening but deteriorate overnight and in the early morning hours, leading to morning hyperglycaemia and hyperlipidaemia. Therefore, one of the main underlying causes of hyperglycaemia and hypertriglyceridemia in T2D might be due to the disruptions in the chronobiology (Heden & Kanaley, 2019). However, this is not a well-established fact. Researchers have reported ways to improve glycaemic control at dinner by comprehending the "second-meal effect." As a result of the metabolic and hormonal reactions to the previous lunch meal, the second-meal effect improves β-cell memory, responsiveness, and glucose tolerance at the dinner meal (Jakubowicz et al., 2021).

In conclusion, the PP glucose response to a meal appears to be influenced by the time of day. These studies demonstrate that the timing of meal consumption has an impact on glucose metabolism in addition to the type and quantity of food consumed. To establish correlation, however, more information from carefully planned epidemiological studies is required.

Temporal Patterns of Nutrient Intake and Glycaemic Control

The literature makes clear that there is a clear circadian pattern that results in a higher PP glucose response to meals at night than in the morning. Given the growing number of people adopting a later chronotype as a result of various lifestyle modifications, it is essential to comprehend how diet can be adjusted to maintain circadian synchronisation and enhance glycaemic control. Glucose levels also seem to be influenced by meal composition as much as by meal timing.

Current evidence indicates that the timing of caloric intake can influence glycaemic management. Research indicates that skipping breakfast or diminishing food intake at the first meal of the day, coupled with high-caloric dinner meals (despite no variation in overall daily caloric intake), leads to a disruption in peripheral clock gene expression and increased daily glucose fluctuations (Marino & Arble, 2023). Furthermore, prior research has demonstrated that elevated caloric consumption during dinner correlates with a heightened risk of diabetes, cardiovascular disease, as well as increased mortality rates from diabetes. Therefore, decreasing energy consumption during dinner may positively impact metabolic health to a certain degree (Baheti et al., 2023). The researchers also found that the eating of carbohydrate-rich dinner meals led to significantly worse PP glucose profile compared to the same meals having been eaten at breakfast, regardless of the content of the meal in terms of the glycaemic index (Haldar et al., 2020). Late meal consumption is associated with an increased intake of calories, primarily from carbohydrates and fat, and can lead to a prolonged PP glucose level increase in the evening, further exacerbating glucose intolerance. Poor glycaemic control has been associated with increased energy uptake past 17:00 in obese adults, and in those with diet-controlled or metformin-controlled prediabetes or T2D, independent of elevated body mass, adiposity, dietary composition, or total caloric food consumption (Díaz-Rizzolo et al., 2024). However, as reported by Nakamura et al. (2021), consuming dinner early (at 18:00) positively influences blood glucose level variability and substrate oxidation in comparison to dining late (at 21:00).

The recent studies suggest that the time of meals can significantly impact metabolic health. Consumption of the foods in the active period of the body, usually in the morning, is linked to increased insulin sensitivity and tolerance to glucose. Conversely, late-night food intake has been attributed to impaired glucose metabolism and increased adipose deposition. These findings highlight the obvious possibility of using chrononutrition as an addition to the traditional dietary interventions (Reytor-González et al., 2025). Altering the late meal composition or decreasing the size of the portions is a critical approach towards the positive adjustment of the PP glycemia.

Temporal Dynamics of Carbohydrate Intake and Glycaemic Response

Regarding circadian rhythmicity and glycaemic control, acute interventional studies have reported that nocturnal carbohydrate consumption positively affects the absorption of dietary carbohydrates, thus resulting in a high PP glucose response the following morning (Henry et al., 2020). Moreover, the order of the intake of the macronutrients has a pivotal impact on the glucose metabolism, especially regarding carbohydrate consumption. The quantity, quality, and frequency of carbohydrate intake all have a direct effect on the PP glycaemia and peripheral insulin sensitivity. It has been indicated that the intake of carbohydrates in the final part of a meal could have a positive effect in regulating the glycaemic responses, providing a lower PP peak at 180 minutes after eating the meal (López-Prieto et al., 2024). When compared to fresh white bread, frozen and reheated white bread leads to lower blood sugar levels. This can be explained by the resistant starch formation during the freezing process (Yahya & Hashim, 2023).

Low glycaemic index (GI) and low glycaemic load (GL) have been demonstrated to yield a better glycaemic control, lipid levels in the blood, blood pressure, and BMI in prediabetic and T2D patients (Peres et al., 2023). There is mounting evidence that intake of carbohydrate-rich meals with high glycaemic index when consumed later in the evening has a more deleterious impact on PP glucose and insulin response than intake of the same meals earlier in the day (Stutz et al., 2024). One study, however, shows that even within the low GI range, the GI value of the food still matters in influencing the PP glucose (Kaur et al., 2020).

A significant molecular distinction occurs in the regulation of melatonin secretion. In humans, melatonin concentrations reach their zenith during the night, suppressing insulin release and facilitating fat oxidation instead of glucose metabolism. This hormonal alteration elucidates the correlation between nocturnal consumption and insulin resistance, as well as metabolic dysregulation in humans (Fuad et al., 2025). One finding explained the role of cortisol in influencing glycaemic management during the day compared to the night, attributable to the circadian rhythmicity of cortisol secretion and heightened activity during daylight, suggesting that inappropriate cortisol secretion may negatively affect glucose homeostasis in T2D (Liang et al., 2024).

The current study indicates that eating a meal at night, even if it contains low-glycemic ingredients, contributes to larger glucose excursions and correspondingly higher insulin levels when compared to an equal meal in the morning (Leung et al., 2019). Collectively, these studies indicate that consuming a low glycaemic index meal, regardless of portion size, enhances glycaemic response in the morning but exerts minimal influence at night. This temporal disparity has been linked to the influence of the endogenous circadian rhythm on glucose metabolism.

Influence of Fat and Protein Timing on Lowering Postprandial Glycaemic Responses to Carbohydrates

Fat and protein have emerged as significant modulators of PP glycaemic responses in relation to carbohydrate intake. However, research indicates that fasting blood glucose levels and hepatic total fat were elevated in rats on a high-fat low-carbohydrate (HFLC) diet. Oral glucose tolerance was similarly lowered; however, insulin sensitivity was not affected. Meanwhile, the HFLC diet was also noted to induce a notably greater gluconeogenesis rate (de Oliveira et al., 2023). As far as protein is concerned, it is noted that protein-rich meals have the potential to positively impact glucose fluctuations at night (Davis et al., 2020). Modifying the macronutrient content of the meal also appeared to be a successful strategy, as noted by Dao et al. (2025), who found that adding protein to meals high in carbohydrates frequently lowers PP glucose excursions in both individuals with or without T2D. This is usually caused by a delay in stomach emptying and an increased insulin response. It is also reported that during the night shift, a nighttime meal that is greater in protein and lower in carbohydrates lowers PP glucose levels, but it has no influence on the metabolic response at the next meal (Cunha et al., 2020). When dairy or plant protein is added to a meal that contains carbohydrates, adults without diabetes have physiologically significant decreases in glucose and increases in insulin (Wolever et al., 2024).

The intake of high glycaemic index starchy foods, such as white rice and white bread, has been associated with the onset of T2D. Consequently, examining the timing of co-ingestion of fats and proteins with carbohydrate-rich diets is an innovative dietary intervention to mitigate glycaemic response. The composition of meals and the consumption of low GI/GL foods, especially when paired with protein and/or fat, diminish PP glucose and insulin responses, hence enhancing insulin sensitivity (Papakonstantinou et al., 2022). Monounsaturated oil, particularly extra virgin olive oil, has been demonstrated to be useful for glycaemic management in persons with T2DM. These advantages are chiefly ascribed to the fatty acid and phenolic makeup of olive oil (Nosić et al., 2023). Evidence from meta-analyses also shows that olive oil consumption is linked to a lower risk of diabetes; in particular, consuming 10–20g of olive oil daily may help prevent and manage diabetes (Du & Zhou, 2025). Eating meat or fish before rice slows down stomach emptying, increases incretin secretion, and enhances PP glucose metabolism, according to a different study that included both healthy adults and people with T2D. Collectively, foods high in fat or protein slow down stomach emptying and encourage the release of incretin. The same study also reviewed that in healthy adults, eating vegetables first, then meat and rice, reduces the PP glycaemic response by increasing glucagon-like peptide-1 (GLP-1) secretion without increasing insulin secretion (Kamemoto et al., 2024). This study's result is consistent with the research conducted by Murugesan et al. (2024) and Imai et al. (2023). Chewing thoroughly reduces PP glucose levels. According to a study, chewing on shredded cabbage increases the release of incretins after meals, but it has no effect on the PP glucose concentration (Kamemoto et al., 2024). Therefore, the sequence of presenting meals and their timing of ingestion has a major impact on regulating glycaemic response.

To sum up, modern research has determined that nocturnal meal intake induces a higher glycaemic excursion and insulin resistance as opposed to daytime intake. People with late chronotypes may benefit from these studies, as they are more likely to experience glycaemic excursions and may learn how to lower their risk of hyperglycemia. This article highlights the nutrient timing and nutrient content (carbohydrate, fat, and protein) interaction on the metabolism of glucose. They also suggest that the temporal patterns of fat and protein in a carbohydrate-rich meal also control the PP glycaemic and insulinemic responses. More recent research has shown that the order of food serving during a meal can also have an effect on glycaemic and insulinemic effects. Together, these observations are easily generalizable to the community-based public-health advocacy targeting the population with a high incidence of T2D and a carbohydrate-based diet.

Table 1. Overview of Research on Meal Timing and Dietary Influences in Glycaemic Regulation

Country	Study year	Number of participants	Study duration	Aim of the study	Targeted population	Main findings	References
Spain	2024	53,053 participants	1 year	To examine the influence of shift work on obesity	31,753 men (17,527 of them working shifts) and 21,300 women (11,281 of them working shifts)	Shift workers exhibit a higher prevalence of obesity and unhealthy lifestyle habits, with men at greater risk	(Tosoratto et al., 2024)
United Kingdom	2014	31 participants (12 men and 19 women)	Randomized controlled trial for 6 weeks	To examine the link between daily breakfast habits (vs. extended morning fasting) and all components of energy balance and human health	Obese and lean individuals	Breakfast was noted to balance the blood sugar levels of later meals, and that chronic morning fasting lowers glucose tolerance	(Afzal et al., 2025)
Japan	2024	4,421 people	1 year	To determine the association of irregular dietary habits with HbA1c and BMI in people with diabetes	People with diabetes aged 20-74 years (844 with T1D and 3,577 with T2D)	Irregular mealtimes are associated with poor glycaemic control in T1D women and are associated with obesity in T2D men	(Shimizu et al., 2025)
India	2024	10 participants	Approximately 1 year	To assess the short-term effect of early	Habitual late eaters with	Modification of dinner time in	(Chauhan et al., 2024)

				dinner on glycaemic control in habitual late eaters with uncontrolled T2D.	uncontrolled T2D	habitual late eaters with uncontrolled T2D improves glycaemic control and insulin resistance in the short term	
China	2023	29,405 participants	Approximately 2 years	To investigate the association between meal frequency and T2DM in resource-limited areas	Permanent populations between the ages of 18–79 years were recruited from rural areas	Reduced meal frequency, especially at dinner, was associated with a lower prevalence of T2DM	(Baheti et al., 2023)
Singapore	2020	34 participants	Randomized crossover trial for approximately 1 year	To assess markers of PP glucose homeostasis following high or low GI meals consumed either at breakfast or at dinner	Healthy, Chinese, elderly volunteers	Carbohydrate-rich meals consumed at dinner lead to significantly worse PP glucose homeostasis than when consumed at breakfast	(Haldar et al., 2020)
Iraq	2023	32 participants (14 males and 18 females)	Randomized controlled trial conducted for 3, 5, and 7 days.	To investigate the impact of reheated white bread and frozen versions on the glycaemic responses of healthy individuals.	Healthy participants, aged 18–50 with a BMI of 18.5-29 kg/m² and fasting blood sugar levels of 75–100 mg/dl.	Frozen and reheated white bread leads to lower blood sugar levels compared to fresh white bread	(Yahya & Hashim, 2023)

Japan	2021	12 participants (2 males and 10 females)	3-day randomized crossover study	To examine whether mild early time-restricted eating improves 24-h blood glucose levels and PP lipid metabolism	Healthy individuals	Eating dinner early (at 18:00) has a positive effect on blood glucose level fluctuation	(Nakamura et al., 2021)
Brazil	2023	Rats	4 weeks	To investigate the effects of an HFLC diet under different energy conditions on glucose homeostasis and hepatic gluconeogenesis	Rats that are being fed an HFLC diet	Fasting blood glucose levels and hepatic total fat were elevated in the HFLC diet.	(de Oliveira et al., 2023)
Australia	2020	A varying number of males and females were recruited from the general population.	2 weeks	To examine whether a high-protein meal attenuates PP glucose at night	Healthy adults	Protein-rich meals have the potential to positively impact glucose fluctuations at night	(Davis et al., 2020)
Brazil	2020	14 males	Controlled, randomized, crossover clinical trial	To compare the acute effect of a high-protein/moderate carbohydrate versus a low-protein/high-carbohydrate diet	Male night workers	A nighttime meal that is greater in protein and lower in carbohydrates lowers PP glucose levels	(Cunha et al., 2020)
Canada	2024	11 meta-analyses	Varied durations	To determine the acute effect of adding protein to carbohydrate on PP responses	Varied populations	When dairy or plant protein is added to a meal, there is a significant decrease in glucose and	(Wolever et al., 2024)

						an increase in insulin	
China	2025	10 studies (4 cohorts and 6 randomized controlled trials)	Varied durations	To evaluate the effects of olive oil consumption on diabetes	50,0000 subjects and 2,0000 diabetics	Consuming 10–20g of olive oil daily may help prevent and manage diabetes.	(Du & Zhou, 2025)
India	2024	25 women	4-week trial	To investigate whether food sequence improves glycaemic control in women with gestational diabetes	Women with gestational diabetes	Prioritizing vegetables before protein and carbohydrates improves glycaemic control and insulin sensitivity	(Murugesan et al., 2024)
Japan	2023	21 participants	Conducted on 3 separate days	To explore whether the speed of eating a test meal influences the PP blood glucose	18 young, healthy women	Food order with vegetables first and carbohydrate last ameliorates PP blood glucose and insulin concentrations even if the meal was consumed at a fast speed.	(Imai et al., 2023)
Japan	2024	19 men	Two 180-minute trials on separate days in a random order	Examined the effects of vegetables consumed in solid versus puree forms on PP glucose metabolism	Healthy young men	Chewing on shredded cabbage increases the release of incretins, but does not affect the PP glucose concentration	(Kamemoto et al., 2024)

Conclusion

Chrononutrition is a developing area in which there is still a lot to learn about how the timing of meal consumption affects glucose homeostasis. The current review indicates that the choice of food is not sufficient enough to determine the PP glycaemic excursions. The influence of the timing of meals on the occurrence and control of T2D is so eminent as to justify the importance of emphasizing the timing of meals, rather than their nutritional content, alone. The evening meal, consisting of a high amount of carbohydrates, has been linked to an increase in PP glucose levels as compared to the same meal eaten in the morning. Therefore, a simple intervention to reduce hyperglycaemia in case of a meal intake in the evening is to change the macronutrient proportions, especially by increasing the protein and fat content. Earlier daytime meals should be encouraged to help people with diabetes. Foods with low GI taken in the morning provide excellent glycaemic responses as opposed to foods taken at night. Glycaemic responses can be reduced by co-administration of fats and proteins with carbohydrate-rich foods. The order of presentation of food had a significant impact on pp glycaemic results, in which vegetables should be eaten first, then meat, and then rice. This strategy has significant potential for lowering pp glucose. Additional studies will make it easier to translate the principles of chronobiology into community-based interventions to stem the current trend of T2D in the global population.

REFERENCES

Afzal, M. A., Noor, M., Shahzadi, N., Saadat, S., Chaudhry, R., & Zafar, M. N. (2025). Case Study of a Patient with Decompensated Type 2 Diabetes Mellitus and Multiple Comorbidities: Implications for Personalised Care and Disease Modulation. *Multidisciplinary Surgical Research Annals*, 3(3), 744-756.

Afzal, M. A., Shahzadi, N., Ahmed, Z., Hyder, A., Saleem, H., Zahra, A., ... & Mukhtar, E. (2025). Breakfast; the most important meal of the day or a myth?. *Biological Times*, 4(2): 20-24.

Afzal, M. A., Habib, A., Ahmed, E., Bukhari, I., & Khan, S. S. (2025). The Importance of Breakfast: Nutritional Significance and Optimal Consumption Patterns. *Biological Times*, 4(6): 7-8.

Ashraf, M. A., Afzal, M. A., Ijaz, M., Arshad, A., Zafar, M. N., Ukkasha, S. M., & Zahid, I. (2025). Financial impact of nutrition on non-communicable diseases in hospital or other healthcare settings. *Biological Times, 4*(9), 20–21.

BaHammam, A. S., & Pirzada, A. (2023). Timing matters: the interplay between early mealtime, circadian rhythms, gene expression, circadian hormones, and metabolism—a narrative review. *Clocks & Sleep*, *5*(3), 507-535. https://doi.org/10.3390/clockssleep5030034

Baheti, B., Liu, X., Wang, M., Zhang, C., Dong, X., Kang, N., ... & Wang, C. (2023). Association between Meal frequency and type 2 diabetes Mellitus in rural adults: a large-scale cross-sectional study. *Nutrients*, *15*(6), 1348. https://doi.org/10.3390/nu15061348

Bautista, J., Ojeda-Mosquera, S., Ordóñez-Lozada, D., & López-Cortés, A. (2025). Peripheral clocks and systemic zeitgeber interactions: from molecular mechanisms to circadian precision medicine. *Frontiers in Endocrinology*, *16*, 1606242. https://doi.org/10.3389/fendo.2025.1606242

Bazzani, A., Marantonio, S., Andreozzi, G., Lorenzoni, V., Bruno, S., Cruz-Sanabria, F., ... & Faraguna, U. (2022). Late chronotypes, late mealtimes. Chrononutrition and sleep habits during the COVID-19 lockdown in Italy. *Appetite*, *172*, 105951. https://doi.org/10.1016/j.appet.2022.105951

Begemann, K., Rawashdeh, O., Olejniczak, I., Pilorz, V., de Assis, L. V. M., Osorio-Mendoza, J., & Oster, H. (2025). Endocrine regulation of circadian rhythms. *npj Biological Timing and Sleep*, 2(1), 10. https://doi.org/10.1038/s44323-025-00024-6

Byun, J. I., Cha, K. S., Jun, J. E., Kim, T. J., Jung, K. Y., Jeong, I. K., & Shin, W. C. (2020). Dynamic changes in nocturnal blood glucose levels are associated with sleep-related features in patients with obstructive sleep apnea. *Scientific Reports*, *10*(1), 17877. https://doi.org/10.1038/s41598-020-74908-x

Chaput, J. P., McHill, A. W., Cox, R. C., Broussard, J. L., Dutil, C., da Costa, B. G., ... & Wright Jr, K. P. (2023). The role of insufficient sleep and circadian misalignment in obesity. *Nature Reviews Endocrinology*, *19*(2), 82-97. https://doi.org/10.1038/s41574-022-00747-7

Chauhan, S., Norbury, R., Faßbender, K. C., Ettinger, U., & Kumari, V. (2023). Beyond sleep: A multidimensional model of chronotype. *Neuroscience & Biobehavioral Reviews*, *148*, 105114. https://doi.org/10.1016/j.neubiorev.2023.105114

Chauhan, Y. V., Gada, J. V., Misra, S., Dhole, C. B., Palekar, A. V., Varthakavi, P. K., ... & Bhagwat, N. (2024). Early Dinner Improves the Glycemic Profile in Habitual Late Eaters With Uncontrolled Type 2 Diabetes Mellitus in the Short Term. *Cureus*, *16*(5). https://doi.org/10.7759/cureus.59504

Cunha, N. B., Silva, C. M., Mota, M. C., Lima, C. A., Teixeira, K. R., Cunha, T. M., & Crispim, C. A. (2020). A high-protein meal during a night shift does not improve postprandial metabolic response the following breakfast: a randomized crossover study with night workers. *Nutrients*, *12*(7), 2071. https://doi.org/10.3390/nu12072071

Dao, G. M., Kowalski, G. M., Bruce, C. R., O'Neal, D. N., Smart, C. E., Zaharieva, D. P., ... & Morrison, D. J. (2025). The Glycemic Impact of Protein Ingestion in People With Type 1 Diabetes. *Diabetes Care*, *48*(4), 509-518. https://doi.org/10.2337/dci24-0096

Davis, R., Bonham, M. P., Nguo, K., & Huggins, C. E. (2020). Glycaemic response at night is improved after eating a high protein meal compared with a standard meal: a cross-over study. *Clinical Nutrition*, *39*(5), 1510-1516. https://doi.org/10.1016/j.clnu.2019.06.014

de Oliveira, M. J., Moreira, E. S., Lucredi, N. C., Bonetti, C. I., de Sá-Nakanishi, A. B., Comar, J. F., ... & Bracht, L. (2023). Effects of a high-fat low-carbohydrate diet under different energy conditions on glucose homeostasis and fatty liver development in rats and on gluconeogenesis in the isolated perfused liver. *Canadian Journal of Physiology and Pharmacology*, *102*(1), 42-54. https://doi.org/10.1139/cjpp-2023-0071

Díaz-Rizzolo, D. A., Santos Baez, L. S., Popp, C. J., Borhan, R., Sordi-Guth, A., Manoogian, E. N., ... & Laferrère, B. (2024). Late eating is associated with poor glucose tolerance, independent of body weight, fat mass, energy intake and diet composition in prediabetes or early onset type 2 diabetes. *Nutrition & Diabetes*, *14*(1), 90. https://doi.org/10.1038/s41387-024-00347-6

Dobrovinskaya, O., Alamilla, J., & Olivas-Aguirre, M. (2024). Impact of modern lifestyle on circadian health and its contribution to adipogenesis and cancer risk. *Cancers*, *16*(21), 3706. https://doi.org/10.3390/cancers16213706

Du, Y., & Zhou, H. (2025). Effect of olive oil consumption on diabetes risk: a dose-response meta-analysis. *Journal of Health, Population and Nutrition*, *44*(1), 135. https://doi.org/10.1186/s41043-025-00866-7

Forouhi, N. G., & Wareham, N. J. (2022). Epidemiology of diabetes. *Medicine*, *50*(10), 638-643. https://doi.org/10.1016/j.mpmed.2022.07.005

Franzago, M., Alessandrelli, E., Notarangelo, S., Stuppia, L., & Vitacolonna, E. (2023). Chrono-nutrition: circadian rhythm and personalized nutrition. *International journal of molecular sciences*, *24*(3), 2571. https://doi.org/10.3390/ijms24032571

Fuad, S. A., Ginting, R. P., & Lee, M. W. (2025). Chrononutrition: Potential, Challenges, and Application in Managing Obesity. *International Journal of Molecular Sciences*, *26*(11), 5116. https://doi.org/10.3390/ijms26115116

Haldar, S., Egli, L., De Castro, C. A., Tay, S. L., Koh, M. X. N., Darimont, C., ... & Henry, C. J. (2020). High or low glycemic index (GI) meals at dinner results in greater postprandial glycemia compared with breakfast: a randomized controlled trial. *BMJ Open Diabetes Research & Care*, *8*(1). https://doi.org/10.1136/bmjdrc-2019-001099

Heden, T. D., & Kanaley, J. A. (2019). Syncing exercise with meals and circadian clocks. *Exercise and sport sciences reviews*, *47*(1), 22-28. https://doi.org/10.1249/JES.0000000000000172

Henry, C. J., Kaur, B., & Quek, R. Y. C. (2020). Chrononutrition in the management of diabetes. *Nutrition & diabetes*, *10*(1), 6. https://doi.org/10.1038/s41387-020-0109-6

Her, T. K., Li, J., Lin, H., Liu, D., Root, K. M., Regal, J. F., ... & Cao, R. (2024). Circadian disruption across lifespan impairs glucose homeostasis and insulin sensitivity in adult mice. *Metabolites*, *14*(2), 126. https://doi.org/10.3390/metabo14020126

Hu, J., Ye, H., Wang, M., Yang, H., Wu, M., Cao, J., ... & Wang, Y. (2025). The Effects of Food on Circadian Rhythm: A Comprehensive Review. *eFood*, *6*(5), e70092. **https://doi.org/10.1002/efd2.70092**

Imai, S., Kajiyama, S., Kitta, K., Miyawaki, T., Matsumoto, S., Ozasa, N., ... & Fukui, M. (2023). Eating vegetables first regardless of eating speed has a significant reducing effect on postprandial blood glucose and insulin in young healthy women: randomized controlled cross-over study. *Nutrients*, *15*(5), 1174. https://doi.org/10.3390/nu15051174

Jakubowicz, D., Wainstein, J., Tsameret, S., & Landau, Z. (2021). Role of high energy breakfast "big breakfast diet" in clock gene regulation of postprandial hyperglycemia and weight loss in type 2 diabetes. *Nutrients*, *13*(5), 1558. https://doi.org/10.3390/nu13051558

Kamemoto, K., Tataka, Y., Hiratsu, A., Nagayama, C., Hamada, Y., Kurata, K., ... & Miyashita, M. (2024). Effect of vegetable consumption with chewing on postprandial glucose metabolism in healthy young men: a randomised controlled study. *Scientific reports*, *14*(1), 7557. https://doi.org/10.1038/s41598-024-58103-w

Kaur, B., Koh, M., Ponnalagu, S., & Henry, C. J. (2020). Postprandial blood glucose response: does the glycaemic index (GI) value matter even in the low GI range?. *Nutrition & Diabetes*, *10*(1), 15. https://doi.org/10.1038/s41387-020-0118-5

Kim, Y. I., Kim, E., Lee, Y., & Park, J. (2025). Role of late-night eating in circadian disruption and depression: a review of emotional health impacts. *Physical Activity and Nutrition*, *29*(1), 18. https://doi.org/10.20463/pan.2025.0003

Koop, S., & Oster, H. (2022). Eat, sleep, repeat–endocrine regulation of behavioural circadian rhythms. *The FEBS journal*, *289*(21), 6543-6558. https://doi.org/10.1111/febs.16109

Lee, E. K. (2022). You Can't Avoid Shift Work? Then Focus on Body Fat Rather than Weight. *Endocrinology and Metabolism*, *37*(5), 756. https://doi.org/10.3803/EnM.2022.501

Leung, G. K., Huggins, C. E., & Bonham, M. P. (2019). Effect of meal timing on postprandial glucose responses to a low glycemic index meal: a crossover trial in healthy volunteers. *Clinical Nutrition*, *38*(1), 465-471. https://doi.org/10.1016/j.clnu.2017.11.010

Liang, Y., Liang, J., Jiang, W., Wang, W., Yang, X., Liu, Y., ... & Shao, J. (2024). Stronger association between morning serum cortisol level and diurnal time in range in type 2 diabetes?. *Diabetology & Metabolic Syndrome*, *16*(1), 290. https://doi.org/10.1186/s13098-024-01515-5

Lloyd, M., Prakash, B. A., Zhao, L., Ni, G., Ru, Y., & Vasudevan, S. R. (2025). Circadian Rhythms in Metabolism and Mental Health: A Reciprocal Regulatory Network with Implications for Metabolic and Neuropsychiatric Disorders. *Current Opinion in Physiology*, 100836. https://doi.org/10.1016/j.cophys.2025.100836

López-Prieto, R. S., Romo-Romo, A., Gómez-Avilés, P., Sharma-Sharma, S., Costilla-Orozco, X., Galán-Ramírez, G. A., & Almeda-Valdés, P. (2024). Time matters: an insight into the relationship between chrononutrition and diabetes. *Revista de investigación clínica*, *76*(2), 80-90. https://doi.org/10.24875/RIC.23000271

Marino, G. M., & Arble, D. M. (2023). Peripheral clock disruption and metabolic disease: moving beyond the anatomy to a functional approach. *Frontiers in Endocrinology*, *14*, 1182506. https://doi.org/10.3389/fendo.2023.1182506

Murugesan, R., Kumar, J., Thiruselvam, S., Leela, K. V., Geetha, K., Satheesan, A., ... & Angelin, M. (2024). Food order affects blood glucose and insulin levels in women with gestational diabetes. *Frontiers in nutrition*, *11*, 1512231. https://doi.org/10.3389/fnut.2024.1512231

Nakamura, K., Tajiri, E., Hatamoto, Y., Ando, T., Shimoda, S., & Yoshimura, E. (2021). Eating dinner early improves 24-h blood glucose levels and boosts lipid metabolism after breakfast the next day: a randomized cross-over trial. *Nutrients*, *13*(7), 2424. https://doi.org/10.3390/nu13072424

Nosić, M., Waisundara, V. Y., & Banjari, I. (2023). Olive oil, fruit and leaves in diabetes mellitus type 2 treatment. *Exploration of foods and foodomics*, *1*(4), 192-205. https://doi.org/10.37349/eff.2023.00015

Ono, D., Weaver, D. R., Hastings, M. H., Honma, K. I., Honma, S., & Silver, R. (2024). The suprachiasmatic nucleus at 50: looking back, then looking forward. *Journal of biological rhythms*, *39*(2), 135-165. https://doi.org/10.1177/07487304231225706

Oros, M., Soyez, F., Moldovan, A. D., Oana, A. R., Voicu, B., & Mihaltan, F. (2025). Sleep and modern life: a population-based study. *Scientific Reports*, *15*(1), 27763. https://doi.org/10.1038/s41598-025-13405-5

Papakonstantinou, E., Oikonomou, C., Nychas, G., & Dimitriadis, G. D. (2022). Effects of diet, lifestyle, chrononutrition and alternative dietary interventions on postprandial glycemia and insulin resistance. *Nutrients*, *14*(4), 823. https://doi.org/10.3390/nu14040823

Peres, M., Costa, H. S., Silva, M. A., & Albuquerque, T. G. (2023). The health effects of low glycemic index and low glycemic load interventions on prediabetes and type 2 diabetes mellitus: a literature review of RCTs. *Nutrients*, *15*(24), 5060. https://doi.org/10.3390/nu15245060

Reytor-González, C., Simancas-Racines, D., Román-Galeano, N. M., Annunziata, G., Galasso, M., Zambrano-Villacres, R., ... & Barrea, L. (2025). Chrononutrition and Energy Balance: How Meal Timing and Circadian Rhythms Shape Weight Regulation and Metabolic Health. *Nutrients*, *17*(13), 2135. https://doi.org/10.3390/nu17132135

Shimizu, M., Oya, J., Kondo, Y., Katamine, A., Hasegawa, Y., & Nakagami, T. (2025). Cross-sectional association of irregular dietary habits with glycemic control and body mass index among people with diabetes. *Journal of Diabetes Investigation*, *16*(2), 285-291. https://doi.org/10.1111/jdi.14347

Solangi, S. P., Channa, N. A., Awan, A. Y., Mugheri, M. H., Soomro, Z. H., & Noorani, L. (2025). Does breakfast skipping alter the serum lipids of university students?. *BMC nutrition*, *11*(1), 51. https://doi.org/10.1186/s40795-024-00970-7

Stutz, B., Krueger, B., Goletzke, J., Jankovic, N., Alexy, U., Herder, C., ... & Buyken, A. E. (2024). Glycemic response to meals with a high glycemic index differs between morning and evening: A randomized cross-over controlled trial among students with early or late chronotype. *European Journal of Nutrition*, *63*(5), 1593-1604. https://doi.org/10.1007/s00394-024-03372-4

Tosoratto, J., Tárraga López, P. J., López-González, Á. A., Vallejos, D., Martínez-Almoyna Rifá, E., & Ramirez-Manent, J. I. (2024). Association of Shift Work, Sociodemographic Variables and Healthy Habits with Obesity Scales. *Life*, *14*(11), 1503. https://doi.org/10.3390/life14111503

Tosoratto, J., Tárraga López, P. J., López-González, Á. A., Busquets-Cortes, C., Obrador de Hevia, J., & Ramirez-Manent, J. I. (2025). Associations Between Shift Work and Insulin Resistance Markers in 53,053 Spanish Workers: A Sex-Stratified Cross-Sectional Analysis Using TyG, TyG-BMI, METS-IR, and SPISE-IR Indices. *Journal of Clinical Medicine*, *14*(13), 4604. https://doi.org/10.3390/jcm14134604

van der Merwe, C., Münch, M., & Kruger, R. (2022). Chronotype differences in body composition, dietary intake and eating behavior outcomes: a scoping systematic review. *Advances in Nutrition*, *13*(6), 2357-2405. https://doi.org/10.1093/advances/nmac093

Van Drunen, R., & Eckel-Mahan, K. (2021). Circadian rhythms of the hypothalamus: from function to physiology. *Clocks & sleep*, *3*(1), 189-226. https://doi.org/10.3390/clockssleep3010012

Wolever, T. M., Zurbau, A., Koecher, K., & Au-Yeung, F. (2024). The effect of adding protein to a carbohydrate meal on postprandial glucose and insulin responses: a systematic review and meta-analysis of acute controlled feeding trials. *The Journal of Nutrition*, *154*(9), 2640-2654. https://doi.org/10.1016/j.tjnut.2024.07.011

World Health Organization. (2024, November 14). *Diabetes* [Fact sheet]. https://www.who.int/news-room/fact-sheets/detail/diabetes

Yahya, B. A., & Hashim, A. M. (2023). Effect of freezing and heating white bread on the glycemic response of healthy individuals. *Journal of Preventive and Complementary Medicine*, *2*(4), 196-201. https://doi.org/10.22034/ncm.2023.409805.1106

Zhao, E., Tait, C., Minacapelli, C. D., Catalano, C., & Rustgi, V. K. (2022). Circadian rhythms, the gut microbiome, and metabolic disorders. *Gastro hep advances*, *1*(1), 93-105. https://doi.org/10.1016/j.gastha.2021.10.008