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Review

Circadian cuisine in synchronizing holistic nutrition and biological rhythms

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Abstract

Human health has been constantly repressed due to the disturbance of homeostasis within the body which is mainly influenced by the harmful environmental conditions. Biological rhythms, internal behavioural and physiological time-based patterns, include circadian, infradian, ultradian, and circannual rhythms which are allow humans to adopt to environmental fluctuations. Biological clock and external cues (zeitgebers) modulate these rhythmic processes. This review is particularly designed to elucidate the mechanisms, classification, and importance of biological rhythms. Circadian rhythms, the 24-hour cycle, governed by the suprachiasmatic nucleus in hypothalamus, has a significant impact on sleep-wake cycle, hormones production and regulation, nutrient metabolism, and cognition. The molecular mechanism of rhythmic regulation is modulated by genes and proteins (CLOCK, BMAL1, PER, CRY, DBP, and REV-ERB). Factors including jetlag, social and cultural norms, shift work, exposure to light, and temperature alterations negatively influence biological rhythms, and consequently cause health disorders such as metabolic abnormalities, sleep and mood disturbance, and immune system reduction. Meal patterns and behaviours are influenced by meal timing, size, and meal frequency in addition to cultural, social, religious, and digital networks, as a result, nutrient deficiency disorders are prevailing, and the effectiveness of disease regimens is also declined. Studies have revealed that the health and wellbeing could be improved by adjusting natural biological rhythms and improving healthcare systems.

INTRODUCTION

Eating patterns and dietary behaviours significantly influence health status, physiological functions, and quality of life. Poor dietary choices and disturbed routines stimulate disease pathogenesis, contributing multiple disorders, e.g., diabetes, malnutrition, hypertension, kidney stones, and obesity (Gator Care, 2024, Saif et al. 2023; Chamorro et al. 2023; Potter et al. 2016). Chronobiology, the science of cyclic physiological and metabolic processes in living organisms, focuses on the impact of biological rhythms in modulating body systems, such as sleep-wake cycle, nutrient's metabolism, hormones synthesis and release, and disease progression (Dollish et al. 2024). This includes the biological clock, circadian rhythms, and external synchronizers (zeitgebers), which govern the internal biological mechanisms, biomorphs, an understanding of which aids in recognizing the influence of chrono-nutrition in the prevention of non-communicable metabolic disorders (McHill & Butler, 2024; Gururaj et al. 2024; Lewandowski, 2023). Factors, such as meal timing and meal composition, individual's age, genetics, and activity levels, and environmental factors, are involved in the pathogenesis of metabolic complications. This review was structured to synchronize eating patterns with circadian rhythms to prevent the progression of metabolic disorders as well as to improve the glycaemic index. Inputs were collected by searching relevant and recent material from PubMed, Sci-Hub, Science Direct, Oxford Journal, ResearchGate, and Google Scholar. This review accentuates circadian rhythms, biological clock, and its associated mechanisms which deteriorate the normal physiology of hypothalamus and other organs. Furthermore, the association among Zeitgebers, week/sleep cycle, and nutrient's metabolism is discussed. Studies relevant to circadian rhythms, meal patterns, immune system response, and chronobiological interventions are the limelight of this review.

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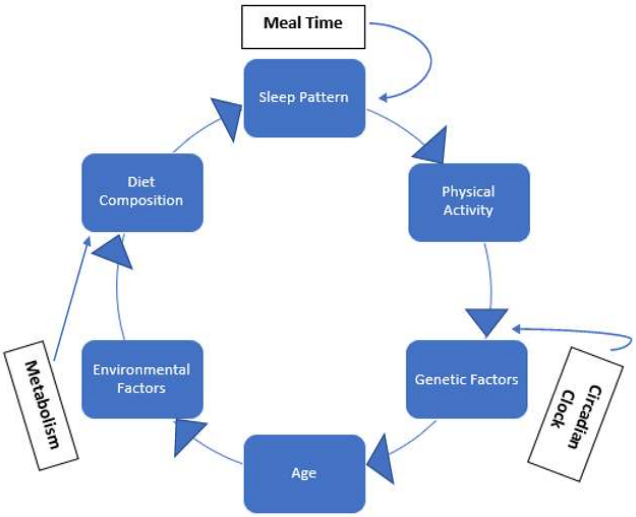


Figure 1. Diagram illustrating factors influencing meal timing, metabolism, and circadian rhythms in chrono-nutrition.

CIRCADIAN RHYTHMS

Day and night cycles are connected to the external physical environment and internal bodily conditions to modulate normal health (Dollish et al. 2024). The internal systems respond in the form of hormone regulation or inhibition, nerve stimulation, and enzymatic reactions to the modifications in the external environment (Adafer et al. 2020). Circadian rhythm, an internal clock of the brain, works as a 24-hour or light/dark cycle which influences the behavioural, physiological, and other metabolic processes of the body (Reddy et al. 2018). It connects the internal bodily processes with the external environment. Fluctuations in external factors can disrupt 24-hour rhythmic cycle, leading to dysregulation of metabolic processes (Khan et al. 2018).

These rhythms are regulated by the biological clocks, located in the suprachiasmatic nucleus (SCN) of the hypothalamus, which synchronize the internal processes with the external environment. The SCN harmonizes the functionality of peripheral rhythms of the tissues and other organs to the central rhythms which enables coordination among the body to forecast shifts in activity levels, food consumption, and sleep patterns throughout the day (Franzago et al. 2023). The regulations stimulated by the external environment ensure cellular performance, including sleep, hormonal secretion, and synthesis. Various environmental factors, such as light, temperature, humidity, pH, air pressure, and air contamination influence the internal system functionality, at times causing multiple disturbances and leading to health problems (Chamorro et al. 2023; Dollish et al. 2024).

Zeitgebers, the external signals, provide synchronization of circadian rhythms to match environmental patterns. The SCN receives signals from light, functioning as the main zeitgeber, to control sleep-wake patterns (Potter et al. 2016). Day and night control the sleep wake cycle as the natural daylight stimulates the body systems to trigger waking. The alignment of body rhythms through natural daylight exposure may become impaired with nighttime lighting, stimulating sleep and sometimes metabolic complications when there is day/night cycle disturbance (Franzago et al. 2023).

Table 1 shows circadian rhythm-based eating patterns. The timing of food consumption acts as a secondary zeitgeber which has an immense impact on peripheral metabolic tissue clocks (Lewandowski, 2023). Late-night consumption disrupts natural body rhythms, glucose metabolism and raises disease susceptibility (McHill & Butler, 2024).

The behavioural zeitgebers are social cues, such as work schedules and social interactions, that regulate eating patterns and sleep cycles (Lewis et al. 2018). Shift work may cause various health issues due to the disturbance of behavioural zeitgebers (Fishbein et al. 2021). Prioritizing zeitgebers may enable us to create lifestyle approaches that will enhance circadian alignment and optimize sleep as well as nutritional patterns to achieve better well-being (Lal et al. 2024). Chronotherapy can involve manipulating environmental and behavioural cues, e.g. light and food, enhancing circadian rhythmicity and counteracting clock misalignment (Palomar-Cros et al. 2023).

Table 1. Circadian rhythm-based eating patterns

Concept	Description	Implications for Health	Examples of Practice	References
Early Chronotypes	Individuals naturally waking up early	Better mental health and lower stress levels	Waking up early and doing morning exercise	(Montaruli et al. 2021)
Late Chronotypes	Individuals tend to stay up late	Increased risk of mood and metabolic disorders	Late night eating and having inconsistent and disturbed sleep routine	(Lotti et al. 2021)
Regular Meal Timings	Consistent meal schedules	Supports circadian rhythm and metabolic balance	Having meals at fixed times daily	(Wehrens et al. 2017)
Nutrient Timing	The timing of macronutrient intake relative to daily activity patterns	Optimizes metabolism and supports physical performance	Consuming carbohydrates after workout and protein in the morning	(Arent et al. 2020)

MOLECULAR MECHANISMS OF THE CIRCADIAN CLOCK

Circadian rhythms regulate biological processes within the body, ensuring that key activities occur at the right times. Clock genes have a significant role in determining the rhythms. Genes and proteins, such as CLOCK, BMAL1, PER, and CRY, modulate the circadian rhythms at the molecular level. Genetic mutations in clock genes may alter circadian rhythms, increasing the chances of disease susceptibility. For example, a mutation in the PER gene is associated with Familial Advanced Sleep Phase Syndrome, characterized by early sleep onset (Chen 2024; Lane et al. 2022).

Figure 2 shows the circadian mechanism at the molecular level which controls physical activities during the day/night cycle. A feedback loop controlling transcription-translation through TTFL regulates the primary operation of the

circadian clock system. The regulatory cycles depend on protein actions between BMAL1, CLOCK, PER, and CRY. Light signals in addition to food signals enable the clock to align with external environmental patterns.

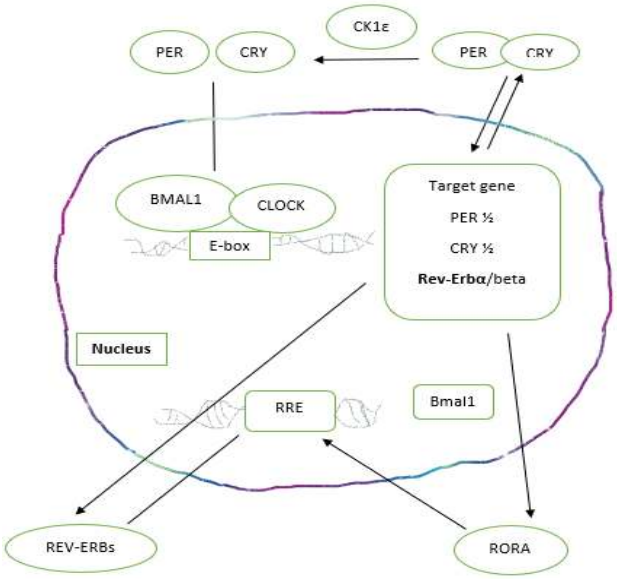


Figure 2. The molecular mechanism of the circadian clock

CLOCK and BMAL1 proteins initiate the transcription of other clock genes, i.e. PER1, PER2, PER3, CRY1, CRY2, REV-ERBα, REV-ERBβ, and DBP, controlling the metabolic processes, including glucose and lipid metabolism, thermogenesis, xenobiotic metabolism, and inflammatory disorders (Dollish et al. 2024; Dalvi & Medithi, 2024; Lal et al. 2024). Glycogenesis and lipogenesis-related genes are active in the daytime while growth, healing, glycogenolysis, and lipolysis-related genes are activated at nighttime (Tippairote et al. 2020). Food intake at the right time can substantially improve energy and nutrient metabolism (Chaix et al. 2019; Moon et al. 2020).

Metabolic regulation depends heavily on circadian rhythms, thereby controlling glucose metabolism alongside fatty acid utilization and energy balance (Lal et al. 2024). These natural patterns maintain the timing of metabolic operations, hormone production, enzymatic actions, and nutrition assimilation throughout the active and resting phases. Individuals experience maximum insulin sensitivity during daytime because the body prepares for eating. Overall metabolic activity becomes slower at night for restful sleep (Dou et al. 2025). Figure 3 describes the role of circadian rhythms in nutrients' metabolism and their impact on metabolic disorders.

People experience disruptions in their natural circadian triggers in recent years due to artificial illumination at night, extended screen time before bed, inconsistent and irregular meal scheduling, and hectic round-the-clock activities. Mismanaged timing between the central SCN and peripheral clocks leads to metabolic dysfunction which in turn raises susceptibility to disease (Chamorro et al. 2023).

Circadian rhythms regulate immune responses by controlling cytokine production, leukocyte trafficking, and inflammatory processes. Sleep disruption can cause inflammatory disorders (Dalvi & Medithi, 2024). Thus, the disrupted circadian rhythm and eating habits of shift workers make them susceptible to inflammatory bowel diseases, gastric and intestinal ulcers, and colorectal cancers (Baxter and Ray, 2020).

Circadian regularity not only regulates normal metabolic health but also prevents disease progression (Lal et al. 2024). Chronobiological interventions like time-restricted eating are proposed to counteract the effects of circadian disruption on metabolism. It limits food intake to specific times of day, aligning with natural metabolic rhythms, and shows promise in improving metabolic health and reducing obesity risks (Gator Care, 2024).

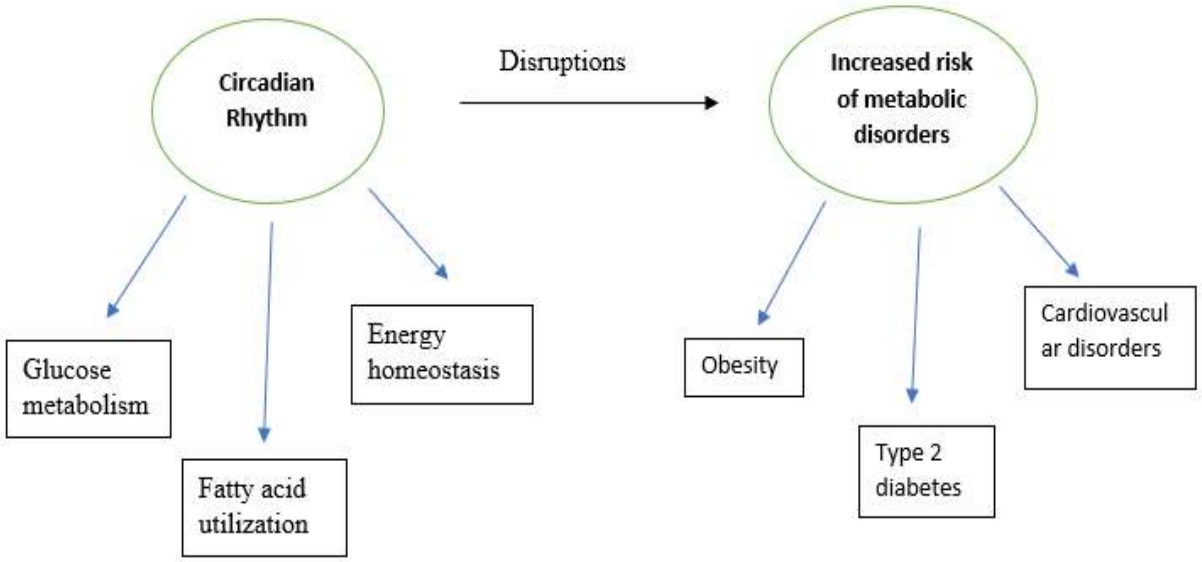


Figure 3. The regulation of metabolism by Circadian rhythm

THE INTERSECTION OF CHRONOBIOLOGY AND NUTRITION

Traditional and cultural practices influence the timing of food intake, meal size, and meal frequency, each critical in maintaining optimal health (Di Francesco et al. 2018; Lopez-Minguez et al. 2019). Biological rhythms are mostly at peak in the morning and early afternoon, which is the appropriate time for food intake (Poggiogalle et al. 2018). Table 2 describes the impact of meal timings on health outcomes. Biological rhythms influence nutritional status (Charlot et al. 2021). Disrupted eating patterns, such as less food consumption during day and more food consumption at night, result in altered postprandial responses and impaired hormonal secretion which influences nutrient metabolism (De Oliveira et al. 2024; Hernández-García et al. 2019), particularly glucose metabolism (Serin & Acar Tek, 2019). Circadian rhythms also regulate the activity of the enzymes involved in the modulation of cholesterol, amino acids, medicines and toxins, glucose, and glycogen (Froy, 2007).

Chrono-nutrition aids in investigating the impact of eating behaviors on health outcomes in three dimensions: meals regularity, meals frequency, and meal timings. Chrono-nutrition is divided into two different categories, including early chronotypes and late chronotypes. Early chronotypes have optimum mental health while late chronotypes are associated with night eating, unhealthy food habits, and their associated metabolic complications (Mentzelou et al. 2024; Díaz-Rizzolo et al. 2024). Metabolic disorders are prevalent among individuals who routinely consume a high fat diet and macronutrients at inappropriate times (Ahluwalia, 2022; Lavallee et al. 2022). The effectiveness of weight loss interventions is higher in individuals consuming meals before 3 pm (Dashti et al. 2019). Figure 4 represents the effectiveness of chrono-nutrition in the management of body weight, blood glucose levels, and ultimately cardiometabolic health.

Table 2. Effects of Meal Timing on Health Outcomes

Meal Timing Practice	Associated Health Risks	Mechanism of Impact	Recommendations	References
Skipping Breakfast	Increased body fat, insulin resistance	Disruption of glucose metabolism	Encourage daily breakfast consumption.	(Alkhulaifi & Darkoh, 2022)
Late-Night Eating	Higher risk of obesity and cardiovascular diseases	Increased caloric intake during inactive hours	Limit eating after 8 PM.	(Alkhulaifi & Darkoh, 2022)
Irregular Meal Timing	Disruption of circadian rhythms, metabolic disorders	Misalignment of biological clocks	Establish a consistent eating schedule.	(Alkhulaifi & Darkoh, 2022)
Night Fasting	Improved metabolic functions	Enhances cellular repair processes	Practice time-restricted eating.	(Alkhulaifi & Darkoh, 2022)

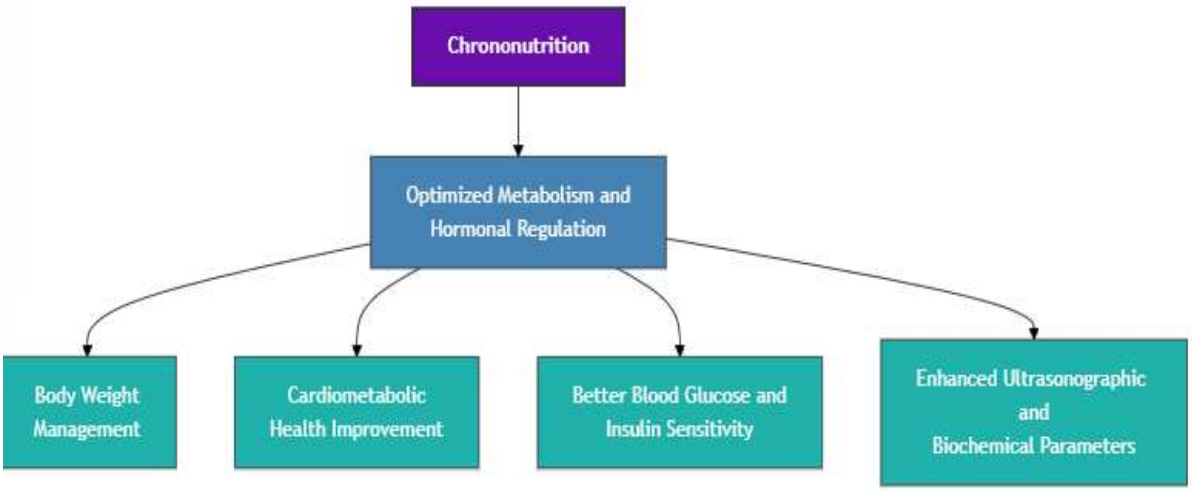


Figure 4: Chrono-nutrition Benefits

IMPACT OF CULTURAL AND SOCIAL ASPECTS OF CHRONO-NUTRITION ON MEAL TIMING

There is an interaction between circadian rhythms, sleep quality, and gut microbiota which can disturb health and nutritional status (Saplontai et al. 2024). Cultural and lifestyle practices have a strong association with the eating patterns of consumers. Diets from the Mediterranean region are appropriate in chronological nutrition, as this diet emphasizes the consumption of large midday meals whereas the Western tradition involves larger meal intakes at dinners (Giovana Longo-Silva et al. 2024). The element of work demands together with urbanization and economic status form the basis through which individuals follow their eating patterns. Urban development and work environments cause people to develop inconsistent eating behaviors (Tiuganji et al. 2020). Furthermore, chronological nutrition varies between economic groups, i.e. higher-income individuals maintain flexibility for healthy food choices while lower-income individuals experience scheduling restrictions and food resource limitations (Booth and Booth, 2011). The impact of cultural influences and lifestyle factors on meal timings and eating habits are described in Table 3. Additionally, technological advancements, particularly digitalization, have an impact on eating patterns and eating schedule. Social media platforms encourage late-night eating through targeted advertisements and featured content (Phoi et al. 2021). Social Jetlag is the inconsistency between an individual's biological clock and his social

schedules which has direct or indirect association in disrupting the natural sleep cycle. Social jetlag causes irregular eating and thereby metabolic complications, such as impaired glucose metabolism, increased lipid profile, weight gain, obesity, insulin resistance, type 2 diabetes mellitus, sleep fluctuations, and cardiovascular impairments (Franzago et al. 2023; Malone et al. 2019; Saplontai et al. 2024).

IMPACT OF MEAL TIMING ON METABOLIC HEALTH

Skipping or consuming meals at inappropriate time disrupts normal physiology of body and can contribute to health problems, e.g., type 2 diabetes mellitus and obesity (Tahara & Shibata, 2014; Nas et al. 2017). This is due to the impaired production of satiety hormones, ghrelin and leptin, which are involved in hunger regulation, energy balance, food consumption, appetite, lipogenesis, and body growth (Mazri et al. 2019; Davis et al. 2022). Meal skipping disrupts the circadian clock, causing elevated glycated hemoglobin levels and postprandial hyperglycemia (Beaulieu et al. 2024; de Assis and Oster, 2021). Skipping breakfast can result in an altered lipid profile, hypertension, and insulin resistance (Challet, 2013). The severity and the risk of cardiovascular disorders is increased in those individuals who have their eating routine late at night (Mazri et al. 2019; Santonja et al. 2023; Cardoso, et al, 2024). A routinely delayed first meal of day increases the risk of cardiovascular disorders by 6% for every hour delay (Gangitano et al. 2021). Figure 5 highlights the impact of delayed eating on circadian rhythms.

Table 3. Cultural Influences on Meal Timings

Culture	Typical Meal Pattern	Chrono-Nutrition Alignment	Challenges
Mediterranean	Larger midday meals	Aligns well with earlier eating times	Evening social gatherings may encourage late meals
Western	Larger dinners	Conflicts with optimal eating timing	Work schedules, reliance on fast food
Middle Eastern	Fasting during Ramadan	Temporary alignment with fasting principles	Irregular eating patterns outside fasting periods
Asian	Frequent small meals	May support better metabolic health	Urbanization and busy lifestyles may disrupt traditional eating patterns
South Asian	Heavy meals at breakfast and dinner	Aligned (partially), but eating late at night can cause disruption	Diet rich in carbohydrates and late-night eating behaviours
Nordic	Focus on whole foods	Maintains energy levels in a stable state	Snacking (due to modern lifestyle)
Latin American	Larger lunch, small dinners	Well-alignment	Late night eating (due to social customs)

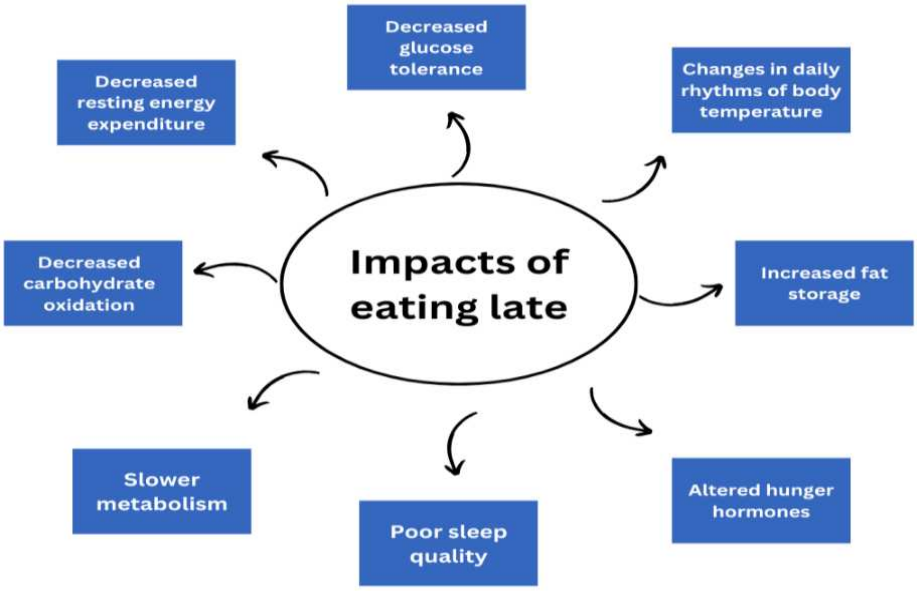


Figure 5. Circadian Rhythm Clock

CHRONOBIOLOGY AND PERSONALIZED MEDICINE

Chronotherapy is a strategy by which the timing of medical treatments and interventions correlates with the biological rhythms of the body (Cardinali et al. 2021; Lee et al. 2021), including light exposure, melatonin administration, and behavioral interventions to stabilize circadian rhythms. For example, administering melatonin in the evening can help realign sleep patterns in individuals with delayed sleep phase disorder. Circadian rhythm plays a role in pharmacokinetics via drug metabolism, absorption, and excretion (Robles-Piedras et al. 2024). The body metabolizes and excretes medications at different rates throughout the day. For instance, liver metabolic activity and renal clearance rates are generally higher during daytime than at night (De Lavallaz & Musso, 2018). Chronotherapy protocols devised for colorectal cancer have resulted in improved

outcomes for treatment administration in the morning than at other hours of the day (Challet, 2013). Chronotherapy has also been proved effective for the treatment of cardiovascular disorders. Blood pressure is at peak in the dawn and adjusting timing of taking antihypertensive medications to coincide with circadian rhythms can enhance their impact on blood pressure (Smolensky et al. 2021).

PERSONALIZED NUTRITION BASED ON CHRONOBIOLOGY

Personalized nutrition linked to chronobiology uses natural rhythms as a basis for dietary intake and as a time course for bettering metabolic health as well as for preventing chronic diseases. The integration of wearable technology and digital tools offers significant potential for personalized chrono-nutrition. Devices monitoring sleep patterns, activity levels, and dietary intakes with chrono-nutrition guidelines are described in Table 4.

Table 4. Potential for personalized nutrition

Technology	Application in Chrono Nutrition	Benefits	Future Directions
Wearable Devices	Monitoring sleep and activity levels	Real-time feedback on adherence	Development of more advanced apps
Genomic Analysis	Tailoring dietary recommendations	Personalized meal timing strategies	Integrating genomic data into nutrition plans
Mobile Apps	Managing Eating Patterns	Support for aligning meals with rhythms	Enhancing user engagement

FUTURE PERSPECTIVES

Chrono-nutrition faces several challenges despite its potential. Variability in individual circadian rhythms and lifestyle factors complicate the development of universal guidelines. Additionally, there is a need for more research to understand the long-term effects and to refine methodologies for integrating chronobiology into practical dietary recommendations. The development of chrono-nutrition strategies based on individual, genetic, and physiological differences should be addressed. Long-term studies should be conducted to investigate the impact of social, cultural, behavioral, and environmental norms on the dietary patterns and nutritional status of individuals. Moreover, technological tools like mobile apps and digital health tools can offer real time feedback and support to individuals in aligning to biological rhythms through eating patterns.

CONCLUSION

The new research fields chronobiology and chrono-nutrition demonstrate that metabolism relies on internal rhythms. Medical treatments that coordinate with natural sleep patterns show promise to work better and cause fewer negative side effects. Finding links between how our environment affects circadian rhythms helps us develop individual methods to support wellness and protect from disease. Healthcare systems will use circadian biology principles to build better health programs for everyone. Effective results depend on our ability to solve circadian treatment problems. Developments in artificial intelligence and machine learning technology can improve the development of customized dietary routines based on time. Medical and dietary approaches to improve health will use scientific developments to match treatments with unique circadian rhythms.

AUTHOR CONTRIBUTIONS

Conceptualization, M.U.K.; Validation, A.M; Investigation, A.F.; Data curation, M.U.K., I.B. and A.A.; Writing draft preparation, M.U.K. and A.F.; Writing—review and editing, R.J; and A.F. Supervision, M.U.K. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN SCIENTIFIC WRITING

Nothing to disclose.

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