Diet Composition and Objectively Assessed Sleep Quality: A Narrative Review

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ABSTRACT
Insufficient sleep is highly prevalent in society and has tremendous negative health consequences. Despite the available treatments, there is continued demand for novel and natural strategies to promote better sleep. Dietary modifications could be a viable new target to improve sleep. A literature review using PubMed was conducted on studies that examined the relationship between diet composition (ie, macronutrients or special diets) and objectively assessed sleep quality. Twenty human studies (6 observational and 14 interventional) published between 1975 and March 2021 met the eligibility criteria and were included. The amount of dietary carbohydrates and fats was associated with both better and worse sleep quality indices. However, the type of carbohydrate and fat was an important factor in these associations, with diets higher in complex carbohydrates (eg, fiber) and healthier fats (eg, unsaturated) being associated with better sleep quality. Diets higher in protein were associated with better sleep quality. In general, diets rich in fiber, fruits, vegetables, and anti-inflammatory nutrients and lower in saturated fat (eg, Mediterranean diet) were associated with better sleep quality. The connection between diet and sleep quality warrants further investigation. Rigorous interventional studies of longer duration assessing the effects of whole foods, rather than isolated nutrients, and under free-living conditions, rather than in a research laboratory setting, as well as mechanistic studies are needed to better understand how dietary patterns relate to sleep quality. Future research could provide insights into whether dietary modifications could be an effective, personalized strategy for improving sleep quality in millions of Americans.
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ABOUT ONE-THIRD OF AMERICANS SUFFER FROM chronic sleep problems.[1] Moreover, nearly 50% of adults complain of feeling sleepy during the day with many reporting its negative impact on their daily activities.[2] Poor sleep quality can be due to poor sleep hygiene or sleep disorders such as insomnia or obstructive sleep apnea (OSA), which are highly prevalent in modern society.[3] Individuals who sleep poorly are more likely to fall asleep while driving or be involved in work-related accidents. Poor sleep quality has also been linked to major adverse health consequences including cardiometabolic diseases and neurodegenerative disorders.[4,5] Current interventions to improve sleep quality include sleep hygiene recommendations (eg, dark sleep environment free of electronics, avoiding excessive caffeine intake)[6,7] and/or specific treatments for sleep disorders (eg, continuous positive airway pressure treatment for OSA, cognitive behavioral therapy and/or pharmacological sleep aids for insomnia).[8-10] Despite the availability of such interventions, there is a continued demand for novel and natural strategies to promote better sleep quality.[11,12] Approximately 80% of individuals using prescription sleep aids report feeling groggy and having concentration difficulties in the day following medication use,[13] which could account for this demand. Some of the novel and natural strategies of interest to improve sleep include dietary supplements and foods/beverages.[14,15] Like sleep habits, Americans also struggle with maintaining healthy dietary habits. The average American consumes excessive amounts of refined grains, saturated fat, and added sugar.[16] Unhealthy diet is thought to explain, for the most part, why about two-thirds of American adults are overweight or have obesity today.[17] Excess weight in turn can lead to poor sleep quality and increase the risk for sleep disorders.[18,19]

Sleep quality can be assessed subjectively by self-report or objectively by sleep monitors. Although self-reported sleep measures are commonly used in most epidemiologic and clinical studies, they are prone to over- or underestimation of sleep as compared with objective assessments. The relationships between diet and sleep were broadly evaluated in 2 prior reviews,[20,21] which included various diets and/or specific food items and subjective and/or objective sleep outcomes. The present narrative review specifically focuses on how diet composition (ie, macronutrients or special diets) relates to objectively assessed sleep quality. A narrative review was conducted because the eligible studies that were included were highly diverse with regards to their methodologies, precluding a systematic review. The findings are summarized from observational and interventional studies where healthy individuals or patients with sleep disorders were assessed in their usual home environment or in a research laboratory. Potential mechanisms that may explain how diet affects objective sleep quality and future research directions are also briefly discussed.

METHODS

Search Strategy and Eligibility Criteria

A literature search was conducted using PubMed with a focus on studies with assessments of diet composition and sleep quality in humans. The search was limited to original research published in English between January 1975 and March 2021 and the following search terms were used: "diet," "sleep," "objective," "polysomnography," and "actigraphy." The search terms were employed in variable order and combinations. In addition, a snowball search was performed using the references of the review article by St-Onge and colleagues.[20] Following the search, the titles and abstracts of the identified articles were screened for relevance, and when appropriate, the full texts were examined for the inclusion and exclusion criteria (Figure 1). The studies were excluded if they involved children or adolescent populations or animal models. Since diet macronutrient composition and whole diets were the primary focus of this review, the studies that examined the effects of specific food items (eg, tart cherry juice, kiwi, fatty fish, milk) on sleep parameters were excluded. The search was limited to objective sleep quality indices,[22] and studies that examined the effects of dietary patterns on other specific sleep metrics (eg, apnea-hypopnea index in OSA) were excluded. Studies that reported only subjective sleep measures (eg, sleep diaries, surveys) or had sleep duration as the primary outcome were also excluded. The studies that primarily investigated sleep patterns in the context of meal timing, fasting, or food quantity were excluded. Eligible studies were categorized as observational (eg, lacking any dietary intervention) or interventional (involving 1 or more experimental diet given to individuals under free-living or laboratory settings). Original research articles were included in this review if they used, in combination with dietary measures, an objective assessment of sleep either by actigraphy or polysomnography. A total of 20 clinical studies (6 observational and 14 interventional) met the eligibility criteria and were included.

Objective Sleep Quality Outcomes

An actigraph is a motion-based monitor worn on the wrist that tracks the sleep-wake states and sleep continuity using automated and validated algorithms.[23] Polysomnography involves recording of electroencephalography via sensors placed on an individual's head and can identify different stages of sleep. Normal sleep architecture is comprised of rapid eye movement (REM) sleep and non-REM sleep. Non-REM sleep stages include N1 and N2 (ie, "light sleep") and N3 (ie, "deep sleep" or "slow wave sleep"). Both slow wave sleep and REM sleep are thought to be restorative and have been implicated in a variety of waking neurobehavioral and physiological functions. Sleep latency is the length of time, in minutes, it takes to transition from wake to sleep. Wake after sleep onset (WASO) is the amount of time, in minutes, spent awake after sleep has been initiated and before final awakening. Sleep efficiency is defined as the percentage of time in bed that is spent asleep. Among adults, optimal (shorter) sleep latency ($\leq$15 minutes), low WASO ($<$50 minutes), few awakenings ($<$4 times), high sleep efficiency ($\geq$85%), and adequate durations of slow wave sleep (25% total sleep time) and REM sleep (20%-25% total sleep time) are well-recognized indicators of good sleep quality.[22]

RESEARCH SNAPSHOT

Research Question: How does diet composition relate to sleep quality assessed by objective tests?

Key Findings: Observational studies utilizing objective sleep measures suggest that higher-quality diets (eg, higher in fiber and protein, rich in fruits and vegetables, and lower in saturated fats) are mostly associated with better sleep quality. Interventional studies indicate that higher-quality diets improve objective sleep quality indices including deep sleep, rapid eye movement sleep, sleep efficiency, sleep latency, and wake after sleep onset.

DISCUSSION

Observational Studies

The literature search identified 6 observational studies that have objectively assessed sleep quality (Table 1). All studies had a cross-sectional design with a total sample size of 1291 individuals. Three studies[24-26] were conducted in healthy populations with normal weight or overweight and no sleep complaints, 2 studies[27,28] included patients with obesity and OSA, and 1 study[29] involved men with obesity and cardiometabolic disease risk. The majority of studies[24,27-29] monitored sleep with a single night in-laboratory polysomnography, and 2 studies[25,26] used 7 to 10 days of home actigraphy. Most studies tracked dietary patterns by self-report (ie, food diaries, validated surveys)[24,25,27-29] with 1 study using a smartphone application.[26] Only 1 study objectively assessed diet by weighing the food in the laboratory.[24] Both acute (1-10 days)[24,26,27] and long-term (1-12 months)[25,28,29] dietary patterns were evaluated.

Carbohydrates and Sleep Quality. Only 1 study by Spaeth and colleagues[24] examined the associations between carbohydrate intake and sleep quality metrics. This study involved a total of 50 men and women and showed that lower carbohydrate intake was associated with shorter sleep latency and more REM sleep. The authors reported that beyond the amount of carbohydrate consumed, the quality of carbohydrate may also be relevant for sleep: more fiber intake was associated with greater deep sleep, an association confirmed by St-Onge and colleagues in their interventional study.[30] Spaeth and colleagues[24] also noted that higher sugar intake was associated with more light sleep. Overall, the findings from this single observational study suggest that diets lower in carbohydrates are associated with better sleep quality, particularly if a greater proportion of the carbohydrates in the diet are refined carbohydrates (eg, white flour products) as opposed to complex or whole carbohydrates (eg, wholegrain).

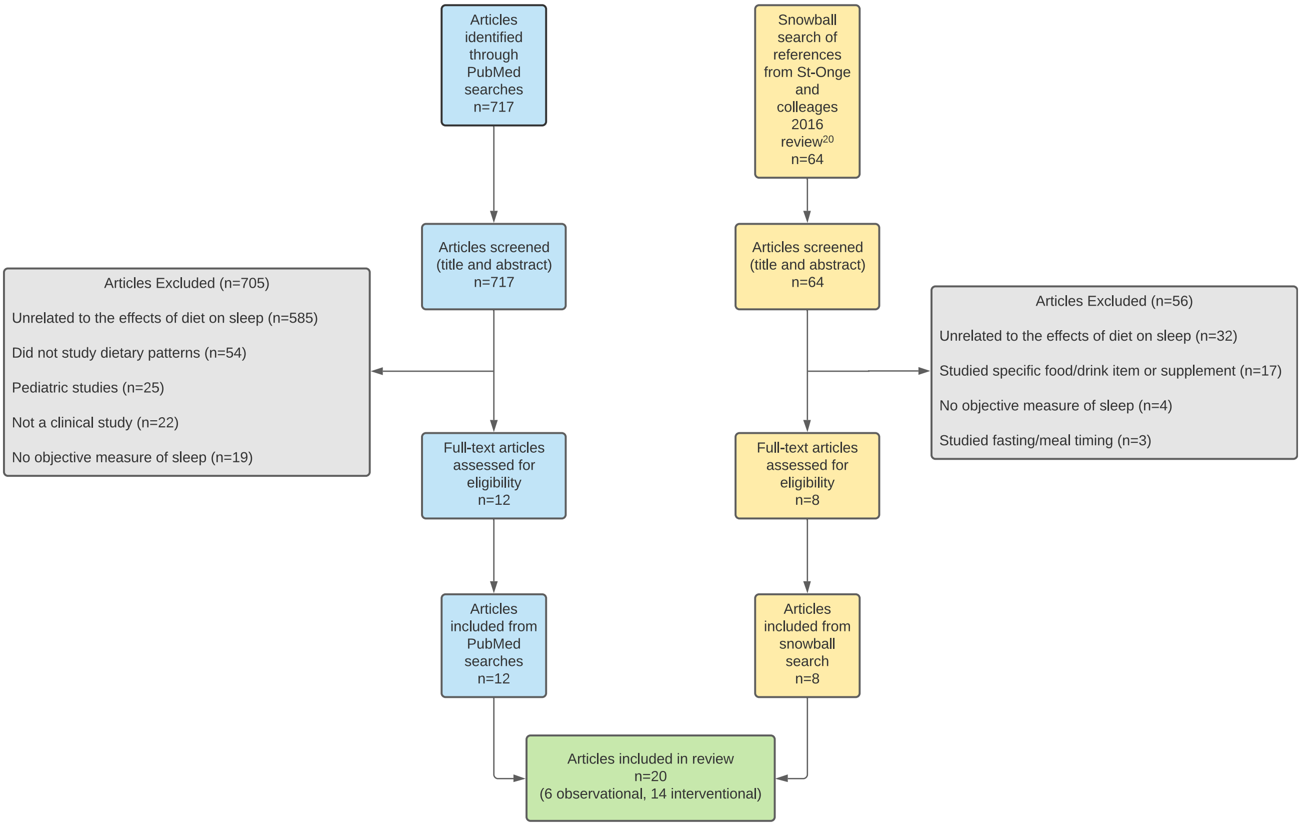

Figure 1. Flow diagram of the literature search and filtering results for a narrative review of the relationship between diet composition and objectively assessed sleep quality.

Protein and Sleep Quality. Three observational studies[25-27] reported that protein intake is associated with sleep quality. Two studies with highly different sample populations[25,27] found a similar association between protein intake and sleep efficiency. In 1 study, lower protein intake was associated with low sleep efficiency among men with OSA.[27] In the other study involving healthy young women, Hashimoto and colleagues[25] observed a 12% lower sleep efficiency with a 1.5% lower protein consumption (12.5% vs 14% of energy). Spaeth and colleagues[24] observed that healthy men and women who consumed more protein had a greater percentage of REM sleep. In contrast to these studies linking higher protein intake to better sleep quality, Falkenberg and colleagues[26] found higher protein consumption associated with lower sleep efficiency, more WASO, and longer sleep latency in healthy professional male athletes. However, the clinical relevance is considered minimal in this study because changes in all sleep quality metrics were less than 1%. The characteristics of participants in this study differed from the participants in the 3 previous studies[24,25,27] in some important ways. These participants were athletes who consumed a very-high-protein diet (25% vs 13%-21% of energy[25,27]) and their sleep duration averaged ∼8 hours per night, compared with ∼6 hours per night.[25,27] The lack of significant sleep changes found in these athletes is in line with findings from Zhou and colleagues,[31] that protein intake beyond 20% confers no additional sleep benefits.

Fat and Sleep Quality. Prior observational studies with subjectively measured sleep quality[32,33] as well as some interventional studies have shown that the amount as well as the type of fat in an individual's diet are associated with sleep parameters. Among the observational studies with objective sleep measures considered in this article, Spaeth and colleagues[24] found that consuming more fat is associated with shorter sleep latency.

Special Diets and Sleep Quality. In 1 study of 784 men at risk of cardiometabolic disease, Cao and colleagues[29] reported that healthy diets promoted shorter sleep latency than unhealthy diets. The diets in this study were characterized as healthy if they consisted of high amounts of vegetables, fruits, and legumes and unhealthy if they contained more processed meat, red meat, snacks, and fast-food items. Many of the foods included in the healthy diet had anti-inflammatory nutrients, such as antioxidants and omega-3 fatty acids. These foods are characteristics of the Mediterranean diet, which has been associated with improved sleep quality in other epidemiological,[34] interventional,[35,36] and observational studies.[37,38] Another observational study by Lopes and colleagues[28] assigned foods an inflammatory index based on known inflammatory markers[39] and found that the inflammatory potential of one's diet was associated with greater self-reported daytime sleepiness, but not with any objectively measured sleep parameters among men and women with OSA.

Table 1. Observational studies on the associations between diet composition and objectively assessed sleep quality

Reference, year, country	Sample size (n)	Study population	Study Design	Sleep assessment	Diet assessment	Main findings
Spaeth and colleagues,[24] 2017, Unites States	50	29 men and 21 women; age: 21-50 y; BMI[a]: 21-28	Cross-sectional	1-night in-laboratory PSG[b]	Weighed food, 1 d before and after PSG	Higher protein and lower carbohydrate intake → ↑[c] REM sleep Higher fiber intake → ↑ slow wave sleep Higher sugar intake → ↑ light sleep Lower carbohydrate and higher fat intake → ↓[d] sleep latency
Cao and colleagues,[29] 2017, Australia	784	Men with cardiometabolic disease risk; age: 35-80 y; BMI: average ∼29	Cross-sectional	1-night home PSG	Food frequency questionnaire over the last 12 mo	Diets rich in vegetables, fruits, and legumes → ↓ sleep latency
De Melo and colleagues,[27] 2019, Brazil	45	Men with OSA[e]; age: 30-55 y; BMI: >30 and <45	Cross-sectional	1-night in-laboratory PSG	Food diary for 3 nonconsecutive d	Higher protein intake → ↑ sleep efficiency
Lopes and colleagues,[28] 2019, Brazil	296	Men and women with OSA; age: 18-60 y; BMI: average ∼31	Cross-sectional	1-night in-laboratory PSG	Food frequency questionnaire over the last 12 mo	Pro-inflammatory diets → ↑ daytime sleepiness, no significant associations with sleep parameters
Hashimoto and colleagues,[25] 2020, Japan	80	Women only; age: 18-27 y; BMI: average ∼20	Cross-sectional	7-d home actigraphy	Diet history questionnaire during the preceding month	Lower protein intake → ↓ sleep efficiency
Falkenberg and colleagues,[26] 2021, Australia	36	Men AFL players[f]; age: average ∼23.5 y; BMI: average ∼24	Cross-sectional	10-d home actigraphy	Meal-Logger smartphone application for 10 d	Higher protein intake → ↑ WASO[g], ↓ sleep efficiency Evening protein intake → ↓ sleep latency

[a]BMI = body mass index (weight-to-height ratio, measured in kg/m^2).
[b]PSG = polysomnography.
[c]↑ = increase.
[d]↓ = decrease.
[e]OSA = obstructive sleep apnea.
[f]AFL = Australian Football League players (professional athletes).
[g]WASO = wake after sleep onset (periods of wakefulness after a designated sleep onset, measured in minutes).

Sleep quality indices	Dietary Factors Associated With Better Sleep[a]		Dietary Factors Associated With Worse Sleep[b]	
	Observational studies	Interventional studies	Observational studies	Interventional studies
Deep sleep	High fiber intake[24]	High fiber intake[30] Low-carbohydrate diet[52] Very-low[c]-carbohydrate diet[47]		High[d]-carbohydrate diet[49] Very-high[e]-carbohydrate diet[51] High saturated fat intake[30]
REM sleep	High-protein diet[24] Low-carbohydrate diet[24]	High-carbohydrate diet[52] Very-high-carbohydrate diet[51]		Low-carbohydrate diet[42] Very-low-carbohydrate diet[47] High-fat diet[49]
WASO		High-carbohydrate diet[43,45] High-fat diet[45] High-protein diet[43] Mediterranean diet[f54]	Very-high-protein diet[g26]	High sugar intake[30]
SOL	Low-carbohydrate diet[24] High-fat diet[24] High vegetable, fruit, and legume intake[29]	High-carbohydrate diet[43] High-GI[h]-carbohydrate intake[48]	Very-high-protein diet[26]	High saturated fat intake[30]
SE		High-protein diet[46]	Low-protein diet[25,27] Very-high-protein diet[26]	

[a]Better sleep refers to more deep sleep, more REM sleep, less WASO, shorter SOL, and higher SE.

[b]Worse sleep refers to less deep sleep, less REM sleep, more WASO, longer SOL, and lower SE.

[c]The very-low-carbohydrate diet employed by Afaghi and colleagues[47] was Atkins-like, with $<1\%$ carbohydrate content.

[d]High carbohydrate diets had a carbohydrate content of 51%-80%.

[e]Very-high-carbohydrate diets had a carbohydrate content $>80\%$.

[f]Mediterranean style diet, but with red meat.

[g]A 25% protein intake in professional athletes.

[h]GI = glycemic index.

Figure 2. Summary of current evidence on diet composition and objectively assessed sleep quality.

In summary (Figure 2), observational studies utilizing objective sleep measures suggest a link between dietary composition and sleep quality. Generally, diets lower in carbohydrates particularly higher in fiber intake are associated with better sleep quality (ie, more deep sleep, more REM sleep, and shorter sleep latency). Diets higher (but not very high) in protein are associated with better sleep quality, marked by higher sleep efficiency both in healthy and OSA populations. Current evidence from healthy individuals and OSA patients also supports the notion that healthier diets higher in fiber and lower in sugar and diets rich in anti-inflammatory foods are associated with better sleep quality. Observational studies that employ home polysomnography or actigraphy are useful because they allow for the study of an individual's habitual dietary patterns, rather than laboratory intakes, which can be influenced by various factors (eg, food availability, type, or amount), while still providing objective sleep data. However, these studies possess some inherent limitations. First, the cross-sectional nature of studies reviewed here does not provide insights on the directionality of the associations between diet and sleep. Second, food data and sleep data were typically not collected sequentially to better interrogate the relationships. Third, dietary assessment was based on self-report in all but 1 study,[24] which is subject to bias. Finally, nearly 90% of participants in these studies were men. Given increasingly recognized sex differences in sleep disturbances,[40,41] more research is necessary to investigate how diet relates to sleep quality in women.

Interventional Studies

The literature search identified 14 studies that have investigated the effects of dietary interventions on objectively measured sleep quality, of which five[42-46] were in-field (Table 2) and nine[30,47-54] were in-laboratory studies (Table 3). The majority included individuals without obesity[30,42,43,45,47-49,51-53] and healthy individuals with no sleep complaints.[30,42-45,47-49,51-54] Only 1 study examined patients with OSA,[50] and another study[46] included individuals with poor sleep quality at baseline.[55] All studies had a within-subject design except 1.[46] Most studies provided controlled diets to participants in random order.[30,43-45,51,53,54] The washout period between dietary interventions varied from 3 days[53] to more than 4 weeks.[54] In total, sleep was measured within a home environment for 150 individuals[42-46] and in a research laboratory for 142 individuals.[30,47-54]

Carbohydrates, Fat, and Sleep Quality. A total of 11 interventional studies[30,42,43,45,47-53] manipulated the carbohydrate and fat content of participants' diets while protein content remained constant. Consequently, high-carbohydrate diets also represent low-fat diets and vice versa.

The interventional diet with the highest carbohydrate content (90% carbohydrate) was implemented by Afaghi and colleagues.[48] Researchers manipulated the glycemic load of dinners while preserving the proportion of energy from carbohydrates. Sleep latency was reduced by ∼9 minutes after 1 night of the high glycemic load (175) dinner compared with a control dinner with low glycemic load (81). However, as the dinners were tested at both 1 hour and 4 hours before bed, with the latter meal timing proving more effective in shortening sleep latency, the effects of the glycemic load on sleep could have been influenced by meal timing.

Phillips and colleagues[51] showed that consuming a very-high-carbohydrate/very-low-fat diet (84% carbohydrate and 5% fat) for 4 days reduced slow wave sleep in healthy young men by ∼18 minutes while REM sleep increased by 33 minutes when compared with a control diet (47% carbohydrate and 43% fat). A decrease in slow wave sleep was also observed, though only in the first sleep cycle, by Yajima and colleagues[49] in 10 young men who were provided with a high-carbohydrate/low-fat diet (80% carbohydrate and 10% fat) for 1 night compared with a very-low-carbohydrate/high-fat diet (12% carbohydrate and 78% fat). The researchers also reported that consuming fewer carbohydrates and more fat reduced REM sleep by ∼8 minutes across all sleep cycles.

Lindseth and Murray[45] implemented a unique design involving both in-field and in-laboratory study periods to test high-carbohydrate, high-fat, and high-protein diets. A total of 44 men and women consumed meals in a supervised laboratory cafeteria setting while continuing daily activities in their usual home environment, and their sleep was measured using wrist actigraphy. Researchers found a reduction in WASO for participants on the high-carbohydrate/low-fat diet (80% carbohydrate and 10% fat) compared with the control diet (50% carbohydrate and 35% fat). However, a decrease in WASO was also observed when participants were given the low-carbohydrate/high-fat diet (25% carbohydrate and 65% fat), which could potentially be explained by the type of fat being consumed, given that a decrease in WASO was also found in participants with a higher polyunsaturated fat intake (≥35% daily fat intake) compared with saturated fat.

Porter and Horne[52] reported an increase in REM sleep by ∼10 minutes with a relatively high-carbohydrate/low-fat bedtime supplement (snack; 72% carbohydrate and 23% fat) as compared with a relatively low-carbohydrate/high-fat supplement (47% carbohydrate and 47% fat) given to a small sample of 6 young men. The low-carbohydrate/high-fat supplement also increased deep sleep by ∼11 to 15 minutes when compared with either the high-carbohydrate/low-fat supplement or the zero-carbohydrate/zero-fat/zero-protein placebo supplement.

Another study by Lindseth and colleagues[43] combining in-field and in-laboratory periods showed reduced sleep latency by ∼5 minutes when participants consumed a high-carbohydrate/low-fat diet (56% carbohydrate and 22% fat) compared with a control diet (50% carbohydrate and 35% fat). Their low-carbohydrate/high-fat diet (22% carbohydrate and 56% fat) elicited no significant changes in sleep parameters relative to the control.

St-Onge and colleagues[30] showed that saturated fat specifically may cause worse sleep quality. Higher saturated fat intakes among 27 healthy adults (7.5% vs 10% of energy) resulted in less slow wave sleep by ∼ 5 minutes and longer sleep latency by ∼12 minutes. This finding is of particular interest, because 10% of energy from saturated fat is still within the US Department of Agriculture's recommended range.[56] However, it is estimated that average Americans consume nearly 12% of their total daily energy in the form of saturated fat.[16] Therefore, these detrimental effects of saturated fat on sleep quality are likely to be even more pronounced in a real-world setting than evidenced in this laboratory study.

Notably, the study by St-Onge and colleagues[30] assessed the impact of self-determined dietary intakes on sleep, and therefore was more representative of usual intakes than the other studies included in this review. Researchers controlled participants intake for 4 days (53% carbohydrate, 31% fat, and 17% protein) then measured participants' ad libitum eating for 1 day, where average intakes comprised 54% carbohydrate, 32% fat, and 14% protein. Participants who consumed more fiber had more slow wave sleep and fewer arousals from sleep. Nocturnal arousals were higher in participants consuming more sugar and more nonsugar/nonfiber carbohydrates (eg, starches). These findings indicate that consuming lower-quality carbohydrates negatively impacts sleep quality.

The most extreme manipulation to participants' carbohydrate and fat intake was by Afaghi and colleagues.[47] They showed that 3 days of very-low-carbohydrate/high-fat meals (<1% carbohydrate and 61% fat) compared with 2 days of

Table 2. Interventional in-field studies on the effects of diet composition on objectively assessed sleep quality

Reference, year, country	Sample size (n)	Study population	Sleep assessment	Diet intervention	Main findings
Kwan and colleagues,[42] 1986, Great Britain	6	Women only; age: 20-23 y; BMI[a]: 19-24	1-night ambulatory PSG[b]	Within-subject design, habitual diet followed by LC-HF[c] diet: 7-d LC-HF diet (10% carbohydrate, 70% fat, 20% protein) vs 7-d habitual diet (49% carbohydrate, 38% fat, 13% protein)	LC-HF diet → ↑[d] REM[e] latency
Lindseth and colleagues,[43] 2013, United States	44	Men and women; age: 18-50 y; BMI: 21-28	4-d actigraphy	Within-subject design, random order, 2-wk washout: 4-d HC-LF[f] diet (56% carbohydrate, 22% fat, 22% protein) vs 4-d LC-HF diet (22% carbohydrate, 56% fat, 22% protein) vs 4-d HP[g] diet (22% carbohydrate, 22% fat, 56% protein) vs 4-d control diet (50% carbohydrate, 35% fat, 15% protein)	HC-LF diet → ↓[h] sleep latency HP diet → ↓ number of awakenings after sleep onset LC-HF diet → no significant differences from control
Lindseth and Murray,[45] 2016, United States	36	32 men and 4 women; age: 18-30 y; BMI: 20-31	4-d actigraphy	Within-subject design, random order, 2-wk washout: 4-d HC-LF diet (80% carbohydrate, 10% fat, 10% protein) vs 4-d LC-HF diet (25% carbohydrate, 65% fat, 10% protein) vs 4-d HP diet (40% carbohydrate, 15% fat, 45% protein) vs 4-d control diet (50% carbohydrate, 35% fat, 15% protein)	HC-LF diets → ↓ wake times (epoch counts) LC-HF diets → ↓ WASO[i] High saturated fat → ↑ wake time High polyunsaturated fat → ↓ wake time HP diet → no significant differences from control
Gwin and Leidy,[44] 2018, United States	13	6 men and 7 women; age: 20-32 y; BMI: 22-30	7-d actigraphy	Within subject design, random order, 3- to 7-d washout: 7-d HP breakfast (42% carbohydrate, 23% fat, 35% protein) vs 7-d no ("skip") breakfast	HP breakfasts → no significant effect on sleep quality
Hudson and colleagues,[46] 2020, United States	51	Men and women with poor sleep[j]; age: 30-69 y; BMI: 25-39	12-wk actigraphy	Parallel design, 12-wk intervention: HP diet (44% carbohydrate, 23% fat, 33% protein) plus 750 kcal/d restriction vs USDA[k]-recommended healthy protein (50% carbohydrate, 30% fat, 20% protein) plus 750 kcal/d restriction	Caloric restriction and HP diets → no significant effect on sleep quality

[a]BMI = body mass index (weight-to-height ratio, measured in kg/m^2).
[b]PSG = polysomnography.
[c]LC-HF = low-carbohydrate/high-fat.
[d]↑ = increase.
[e]REM = rapid eye movement sleep.
[f]HC-LF = high-carbohydrate/low-fat.
[g]HP = high protein.
[h]↓ = decrease.
[i]WASO = wake after sleep onset (periods of wakefulness after a designated sleep onset, measured in minutes).
[j]Poor sleep was defined as Pittsburgh Sleep Quality Index sleep score ≥5.
[k]USDA = US Department of Agriculture.

Table 3. Interventional in-laboratory studies on the effects of dietary composition on objectively assessed sleep quality

Reference, year, country	Sample size (n)	Study population	Sleep assessment	Diet intervention	Main findings
Phillips and colleagues,[51] 1975, Great Britain	8	Young men only; BMI[a]: normal weight	3-night PSG[b]	Within-subject design, random order, 2-wk washout: 2-d HC-LF[c] diet (84% carbohydrate, 5% fat, 11% protein) vs 2-d LC-HF[d] diet (25% carbohydrate, 56% fat, 19% protein) vs 2-d control diet (47% carbohydrate, 43% fat, 10% protein)	HC-LF diet → ↓[e] slow wave sleep, ↑[f] REM[g] sleep LC-HF diet → ↑ REM sleep[h]
Porter and Horne,[52] 1981, Great Britain	6	Young men only; BMI: normal weight	3-night PSG	Within-subject design, random order, 3-night washout: 3-night placebo supplement[i] (0% carbohydrate, 0% fat, 0% protein) vs 3-night LC-HF supplement (47% carbohydrate, 47% fat, 6%) vs 3-night HC-LF supplement (72% carbohydrate, 23% fat, 5% protein)	LC-HF supplement → ↑ slow wave sleep HC-LF supplement → ↑ REM sleep, ↓ light sleep and wake
Driver and colleagues,[53] 1999, South Africa	7	Men only; age: 20-24 y; BMI: average ∼23	3-night PSG	Within-subject design, random order, 3- to 5-d washout: 1-night high-energy dinner (42% carbohydrate, 37% fat, 21% protein) vs 1-night average-energy (control) dinner (61% carbohydrate, 13% fat, 26% protein) vs 1-night no dinner	No significant effect of dietary intervention on objective sleep quality
Afaghi and colleagues,[48] 2007, United States	10	Men only; age: 18-35 y; BMI: 18.5-25	3-night PSG	Within-subject design, random order, 1-wk washout: 1-night high glycemic load dinner (90% carbohydrate with glycemic load of 175, 2% fat, 8% protein) vs 1-night low glycemic load dinner (90% carbohydrate with glycemic load of 81, 2% fat, 8% protein = 81)	High-GL[j] dinner → ↓ sleep latency[k]
Afaghi and colleagues,[47] 2008, United States	14	Men only; age: 18-35 y; BMI: average ∼23	4-night PSG	Within-subject design, HC-LF diet followed by VLC[l] diet: 2-night VLC dinner (1% carbohydrate, 61% fat, 38% protein) vs 3-d HC-LF (control) dinner (72% carbohydrate, 16% fat, 13% protein)	VLC diet → ↑ slow wave sleep, ↓ REM sleep
Yajima and colleagues,[49] 2014, Japan	10	Men only; age: average ∼25 y; BMI: average ∼23	2-night PSG	Within-subject design, random order, 5- to 18-d washout: 1-night HC-LF dinner (80% carbohydrate, 10% fat, 10% protein) vs 1-night LC-HF dinner (12% carbohydrate, 78% fat, 10% protein)	No significant effect of HC-LF or LC-HF dinner on whole night sleep quality HC-LF dinner → ↓ slow wave sleep in the first sleep cycle

(*continued on next page*)

RESEARCH

Table 3. Interventional in-laboratory studies on the effects of dietary composition on objectively assessed sleep quality (*continued*)

Reference, year, country	Sample size (n)	Study population	Sleep assessment	Diet intervention	Main findings
Trakada and colleagues,[50] 2014, Greece	19	Men and women with OSA[m]; age: 28-69 y; BMI: 27.5-55.9	2-night PSG	Within-subject design, light dinner followed by fatty dinner: 1-night fatty dinner (20% carbohydrates, 70% fat, 10% protein) vs 1-night light dinner (49% carbohydrates, 18% fat, 32% protein)	Fatty dinner → ↑ OSA severity but no significant effect on other sleep parameters
St-Onge and colleagues,[30] 2016, United States	27	Men and women; age: 30-45 y; BMI: 22-26	5-night PSG	Within-subject design, random order, 3-wk washout: 2-d ad libitum diet (54% carbohydrate, 32% fat with 10% saturated fat, 14% protein) vs 4-d control diet (53% carbohydrate, 31% fat with 7.5% saturated fat, 17% protein)	High saturated fat and low fiber → ↑ light sleep, ↓ slow wave sleep Higher sugar and nonsugar/ nonfiber carbohydrates[n] → ↑ nocturnal arousals
O'Connor and colleagues,[54] 2018, United States	41	13 men and 28 women; age: 25-37 y; BMI: 30-69	5-wk actigraphy	Within-subject design, random order, ≥4-wk washout: 5-wk Red-Med diet[o] (500 g/wk of red meat, about 13% total daily protein) vs 5-wk Med-Control diet[o] (200 g/wk red, about 5% total daily protein)	Higher intake of red meat → ↓ WASO[p]

[a]BMI = body mass index (weight-to-height ratio, measured in kg/m^2).
[b]PSG = polysomnography.
[c]HC-LF = high-carbohydrate/low-fat.
[d]LC-HF = low-carbohydrate/high-fat.
[e]↓ = decrease.
[f]↑ = increase.
[g]REM = rapid eye movement.
[h]The observed increase in REM sleep was not as great as that observed after the HC-LF diet.
[i]Methylcellulose placebo capsule.
[j]GL = glycemic load.
[k]↓↓ sleep latency when meals consumed 4 hours before bed compared with 1 hour before bed.
[l]VLC = very-low-carbohydrate.
[m]OSA = obstructive sleep apnea.
[n]Nonsugar/nonfiber carbohydrates = starches.
[o]Meals were matched for energy and other macronutrients.
[p]WASO = wake after sleep onset (periods of wakefulness after a designated sleep onset, measured in minutes).

high-carbohydrate/low-fat meals (72% carbohydrate and 16% fat) increased slow wave sleep by ∼15 minutes and decreased REM sleep by ∼15 minutes.

Protein and Sleep Quality. The associations seen between protein intake and sleep quality in observational studies[24,25,27] were mostly supported by evidence from interventional studies. In a study done by Hudson and colleagues[46] investigating 51 men and women reporting poor sleep, consuming more protein (33% vs 20% of energy) within a 12-week weight-loss diet plan (750 kcal/d restriction) caused a slight improvement in sleep efficiency of 1%. Other interventional studies have found protein intake to reduce WASO: Lindseth and colleagues[43] found that 4 days of a high-protein diet (56% protein) reduced WASO in healthy adults when compared with the control diet (15% protein). Similarly, Gwin and Leidy[44] found that total sleep time, but not WASO, decreased by 36 minutes in young adults consuming a high-protein (35% protein) breakfast compared with those who skipped breakfast. However, the sleep efficiency after sleep initiation was almost identical between high-protein and control conditions in this study, suggesting that the reduction in sleep time was not detrimental to overall sleep quality.

Special Diets and Sleep Quality. Some interventional studies tested extremes of dietary macronutrient profiles with the intention of mimicking a specific dietary regimen. For example, Afaghi and colleagues[47] designed their low-carbohydrate/high-fat/high-protein experimental meals to reflect the Atkins diet and found that this dietary pattern increased deep sleep. Other studies did not include such major dietary modifications in their design. O'Connor and colleagues[54] studied 41 men and women undergoing Mediterranean-style diets that varied in their amount of lean, unprocessed red meat for a period of 12 weeks. Their so-called "Red-Med diet" provided 13% of total daily protein from beef or pork, and the "Control-Med" diet provided only 5% of total daily protein from these animal sources and more protein from poultry and legumes. Otherwise, these 2 special diets were very similar, reflected a typical Mediterranean-style diet, and had macronutrient proportions within a range more likely to be seen in the diets of free-living adult populations. The only sleep quality metric that differed between the 2 diets was WASO, which decreased by 4 minutes under the Red-Med diet. Future interventional studies of extended duration might prove useful in understanding the effects of diet on sleep quality in free-living populations, in which individuals maintain dietary habits over longer periods of time.

In summary (Figure 2), interventional studies are useful to indicate directionality to the relationships between diet and sleep quality. The current evidence suggests that very-high- and high-carbohydrate/low-fat diets reduce sleep latency[43] and WASO[45] and increase REM sleep[51,52] but reduce deep sleep.[49,51] By contrast, lower-carbohydrate/higher-fat diets reduce REM sleep[42,47,49] and increase deep sleep.[47,52] In the only interventional study that involved patients with OSA, fatty dinner increased disease severity, but no significant effect was observed on other sleep quality parameters. Interventional data also suggest that consuming more protein could improve sleep quality by decreasing WASO,[43] but whether protein influences other sleep indices requires further study. The 2 special diets considered here (Atkins-like[47] and Mediterranean[54]) appear to promote better sleep quality by increasing deep sleep and reducing nightly waking, respectively. Differences in findings between studies reported above could result from multiple factors, including the type of control diets employed and attention to quality of carbohydrates and fats. Overall, studies show that improvements in sleep are observed when carbohydrates and fat are of good nutritional quality (nonrefined carbohydrates and fiber and unsaturated fats).

Potential Mechanisms for the Influence of Diet on Sleep Quality

The underlying mechanisms for the impact of diet on sleep quality are largely unknown, although multiple pathways have been postulated. An amino acid, tryptophan (Trp), specifically its ratio relative to large neutral amino acids (LNAAs) in the blood, appears to be a potential mediator in the connection between diet and sleep. Trp is a precursor of the synthesis of the serotonin neurotransmitter and melatonin hormone, which are both integral to sleep-wake regulation. Researchers[25,48,52] have proposed that diets that increase the Trp:LNAA ratio allow for greater synthesis of these sleep-promoting factors. When Trp levels are increased, the amino acid can surpass other LNAAs for transport across the blood-brain barrier (BBB).[21] Once across, Trp is converted to serotonin, which in turn regulates sleep-wake. Higher-carbohydrate meals are thought to increase the amount of Trp in the blood relative to other LNAAs by promoting the uptake of LNAAs into skeletal muscle through an insulin-mediated mechanism.[57] This effectively elevates the Trp:LNAA ratio and allows more Trp transport across the BBB for serotonin synthesis. There is also evidence that high-protein meals could promote sleep quality by increasing levels of plasma Trp, but only if the protein ingested does not also increase plasma levels of other LNAAs.[58] Zhou and colleagues[31] found no difference in plasma Trp:LNAA ratio between diets containing 10%, 20%, and 30% protein and attributed this to an increase in both Trp and LNAAs. Thus, it seems that a balanced diet with protein and carbohydrates or consuming specific Trp-rich foods (eg, beans, eggs) is most effective in improving sleep quality through Trp-mediated mechanisms. It is accepted that the effects of Trp on sleep-wake patterns depend on its transport across the BBB, and thus its levels relative to other LNAAs. Yet Trp is also converted to melatonin, via serotonin, in the pineal gland, which resides outside the BBB. Thus, the production of melatonin in the pineal gland should not be influenced by any transport competition between Trp and other LNAAs across the BBB and rather should respond directly to plasma concentrations of Trp.[59] More research is needed to elucidate the potential role of Trp in sleep quality as a precursor to serotonin and melatonin syntheses through BBB-dependent or -independent mechanisms.

Other humoral factors have also been postulated as mediators of improved sleep quality after certain diets. Growth hormone is primarily released during slow wave sleep, and its secretion is suppressed by carbohydrates. This has led researchers[51] to suggest that very-high-carbohydrate meals might reduce slow wave sleep via alterations in growth hormone. Ghrelin, an appetite-stimulating hormone, has been postulated as a sleep-promoting factor.[60] Ghrelin levels normally rise preceding a meal or during a prolonged fast, and fatty foods can further elevate ghrelin levels.[61] Aside from its role in energy balance, 1 study concluded that ghrelin was a sleep-promoting factor after observing that hourly administration of ghrelin (from 2200 to 0100 hours) to healthy adult men increased their deep sleep by 17 minutes.[62] Cholecystokinin release is stimulated by fat intake and has been shown to promote slow wave sleep in animal models.[63,64] This has not been confirmed in humans; however, there is evidence[65] supporting associations between subjective feelings of sleepiness and higher cholecystokinin.

Additionally, Trp-independent mechanisms invoke one's diet for sleep promotion. Healthier diets, consisting of greater proportions of plant foods (fruits, vegetables, grains, seeds, legumes) and vegetable oils, could be associated with improved sleep quality via the synthesis and secretion of serotonin and melatonin.[25,66,67] These foods also provide exogenous serotonin and melatonin and contain higher levels of fiber. These foods promote tissue repair and brain restoration; and since there is empirical evidence[68] that these processes occur during slow wave sleep, a healthy diet could encourage the body to extend its time in this sleep stage.

Finally, research has accumulated over the past several years implicating a potential role of gut microbiome in sleep.[69] For example, 1 study[70] has found that high microbiome diversity (eg, a broad range of bacteria presence in gut) is correlated with better sleep efficiency, greater total sleep time, and less WASO. Although individuals' gut microbiota is highly personalized, there is evidence that dietary habits and patterns can cause both transient and long-term changes to an individual's microbiota: fiber and fat content of the diet appear closely linked to changes in microbiota species, with high-fiber diets promoting and high-fat diets diminishing diversity.[71] This notion is in line with the evidence suggesting that diets higher in fiber and lower in fat can promote better sleep quality. More research[72] may reveal microbiome as a potential target along with dietary manipulation to improve sleep quality.

SUMMARY AND FUTURE DIRECTIONS

In summary, the current evidence from observational and interventional studies suggests that healthier diets and good, objectively assessed sleep quality occur concurrently (Figure 2). High-carbohydrate (ie, carbohydrate content >50% and <80%) and very-high-carbohydrate (ie, carbohydrate content >80%) diets are associated with poorer sleep quality marked by less deep sleep. However, consuming more carbohydrates is also associated with better sleep quality (ie, more REM sleep, less WASO, and shorter SOL [sleep onset latency]). Notably, carbohydrate quality (eg, the proportion of complex vs simple carbohydrates in one's diet) also matters in sleep quality. Consuming more fiber is associated with better sleep quality (ie, more deep sleep), and high sugar intakes are associated with worse sleep quality (ie, more WASO). Similarly, fat quality is also an important consideration for sleep quality. Although consuming more saturated fat is associated with poorer sleep quality, marked by less deep sleep and longer SOL, consuming healthier fats (eg, polyunsaturated fat) is associated with better sleep quality denoted by less WASO and shorter SOL. Diets higher in protein are associated with better sleep quality (ie, more REM sleep, higher sleep efficiency, and less WASO). When overall diet, rather than discrete macronutrients, is considered, those rich in fiber, fruits and vegetables, and anti-inflammatory nutrients and lower in sugar and saturated fat are associated with better sleep quality. Of note, 3 studies included in this review[27,28,50] studied patients with OSA, and future research is needed to rigorously examine the effects of diet composition on objective sleep quality in patients with OSA and other populations with sleep disorders. In a recent narrative review, Binks and colleagues[21] examined the link between diet and sleep in healthy individuals focusing primarily on foods items and dietary supplements. The authors also briefly discussed the effects of macronutrients on subjective and objective sleep parameters referencing some studies[30,43,45,47-49,53] that were included in the current review and have reached similar conclusions. Notably, the current narrative review has additional studies[24-29,42,44,46,50-52,54] and greatly expands the discussion on the effects of macronutrient composition of diet on objective sleep quality both in healthy individuals and patients with sleep disorders. Food timing, circadian rhythms, and chrononutrition are increasingly recognized as key aspects of dietary patterns, and more research exploring how these aspects of eating behaviors affect sleep quality is warranted.[73]

The beneficial impact of diet on objectively assessed sleep quality metrics (eg, 5- to 12-minute improvement in sleep latency), evidenced in the interventional studies reviewed here, could be viewed as minimal or of little clinical significance. However, it is important to note that these effects sizes are comparable to, if not exceeding, those achieved through sleep-enhancing medications.[74] Thus, there is a need for rigorous research in real-life settings to investigate whether dietary modification could be an alternative nonpharmacological approach for sleep improvement. Indeed, this narrative review uncovered important gaps in knowledge on the connection between diet and sleep quality that warrant further investigation. Most published interventional studies focused on extreme experimental diets, which would not be sustainable in real life. Although these laboratory studies provided insights into the associations between dietary macronutrients and objective sleep quality, they cannot inform about how diets impact objective sleep quality while individuals are living in their natural home environment. Therefore, interventional studies using whole-food diets under free-living conditions are needed to better understand how dietary patterns that align with public health recommendations influence to sleep quality. More research is also needed to elucidate the underlying biological pathways for the connections between diet and sleep quality. A better understanding of the connection between diet and sleep quality at a population level is important and can pave the way for personalized dietary interventions as a viable option to promote better sleep quality. Although waiting for more evidence from future research on how diet composition relates to sleep quality, dietitians and other health care providers should continue to encourage their patients to practice healthy dietary habits and educate the public on the multitude of potential benefits to maintaining a healthy diet.

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AUTHOR CONTRIBUTIONS

K. Wilson, E. Tasali, and M.-P. St-Onge designed the review. K. Wilson performed the literature search and wrote the initial draft of the review. E. Tasali and K. Wilson interpreted data and wrote the manuscript. M.-P. St-Onge edited the manuscript for critical intellectual content. All authors gave final approval of the version to be published.