



Prospects for developing sleep-related functional foods: Use of electroencephalography for objective sleep measurement

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Abstract:

The development of sleep-enhancing food products can improve sleep quality. Understanding the relationship between food consumption and sleep is essential for selecting suitable ingredients for these products.

Electroencephalography is a valuable tool for identifying foods and raw materials used in sleep-promoting products, providing critical insights into their effectiveness.

This review examined the relationship between food consumption and sleep based on research from 2004 to 2024 utilizing electroencephalography tools in human and animal models. The effects of food intake on sleep were examined during the initial stage, slow-wave sleep, and the subsequent stage, rapid eye movement, with measurable parameters recorded. The intake quantity and concentration of specific foods or ingredients were analyzed in human and animal models, considering both normal sleep patterns and sleep disorder models. The analysis revealed that foods associated with sleep, as determined by electroencephalography testing, can be classified into six categories: essential oils, Chinese herbal medicines, plant and fungi extracts, tea and cocoa, probiotics and prebiotics in fermented foods, and food supplements. All the food types predominantly influenced the initial stage of sleep, specifically slow-wave sleep during non-rapid eye movement. In contrast, foods containing Chinese herbal medicines or extracts demonstrated a significant effect on the rapid eye movement stage. These findings provide valuable insights into the development of functional foods aimed at improving sleep quality.

Keywords: Sleep monitoring, slow-wave sleep, rapid eye movement sleep, sleep-enhancing food products, functional food development, sleep quality

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INTRODUCTION

Health maintenance in humans encompasses various approaches, one of which is to consume foods that promote overall well-being. Numerous food products not only contribute to general health but also modulate specific physiological functions within the human body. Among these, functional foods with bioactive compounds that influence sleep have been the focus of extensive research. These compounds may facilitate sleep onset or, conversely, disrupt the sleep process by interfering with natural sleep mechanisms. The functional food market has demonstrated remarkable growth, with

its global value estimated to increase from USD 119.2 billion in 2024 to USD 165.8 billion by 2029¹.

Electroencephalography (EEG) has been employed as a critical tool to investigate the relationship between food consumption and sleep. This technique measures brain wave patterns to elucidate correlations with sleep quality and is utilized in both animal and human studies.

¹ Functional food ingredients market by type (probiotics, protein & amino acids, phytochemicals & plant extracts, prebiotic, omega-3 fatty acids, carotenoids, vitamins), application, source, form, health benefits and region: global forecast to 2029. Markets and Markets. [cited 2025 Feb 10]. Available from: <https://www.marketsandmarkets.com/Market-Reports/functional-food-ingredients-market-9242020.html>

Sleep is a critical physiological function explained by several interrelated theories, including the inactivity theory, restoration theory, energy conservation theory, and brain plasticity theory [1]. According to the American Academy of Sleep Medicine, sleep is divided into two main phases: slow-wave sleep (SWS) and rapid eye movement (REM) sleep. These phases are distinguished by specific brain-wave patterns, muscle activity, and eye movements. Slow-wave sleep is further divided into three stages, the first known as non-rapid eye movement [2]. Slow-frequency brainwaves, such as theta and delta waves, dominate during slow-wave sleep. In contrast, higher-frequency waves, such as alpha, beta, or gamma waves, predominate in the wake state, depending on activity levels. REM sleep is regulated by REM-on neurons, which induce this stage through superior colliculus stimulation to generate rapid eye movements, cholinergic neuron activation in the cortex to produce beta wave-dominant brain activity, and motor neuron inhibition of the medullary reticulospinal tract to induce muscle atonia. These mechanisms collectively underscore the complexity of sleep regulation and its physiological foundations [3].

In addition to EEG, electromyography (EMG) and electrooculography are standard techniques used for sleep staging. In recent years, polysomnographic devices that emphasize EEG and EMG have advanced significantly, enabling the measurement of objective sleep parameters through automatic sleep scoring algorithms [4].

In animal studies, cortical electrodes are chronically implanted and securely attached to the skull using invasive techniques for sleep monitoring [5]. In human applications, setups range from full laboratory configurations to portable devices with a limited number of electrodes, providing flexibility for various research contexts [6].

Theoretically, EEG can differentiate between the stages of slow-wave sleep: theta waves are prominent during SWS stage 1, sleep spindles and K-complexes characterize the transition to SWS stage 2, while high-voltage, slow-frequency delta waves dominate in SWS stage 3. In animal studies, the sleep stages are typically categorized into SWS, REM, and wake states. They are often analyzed using fast Fourier transform techniques to quantify brainwave activity [7].

In this review, we compiled and analyzed data on foods associated with sleep regulation to enhance their understanding and provide a foundation for their development. This review was conducted using a systematic approach, incorporating research articles published between 2004 and 2024.

STUDY OBJECTS AND METHODS

Electroencephalography is a valuable tool for identifying foods and raw materials used in sleep-promoting products, providing critical insights into their effectiveness.

Methods. The data for our systematic review were collected from the electronic databases such as Scopus, PubMed, and Google Scholar as described in Fig. 1.

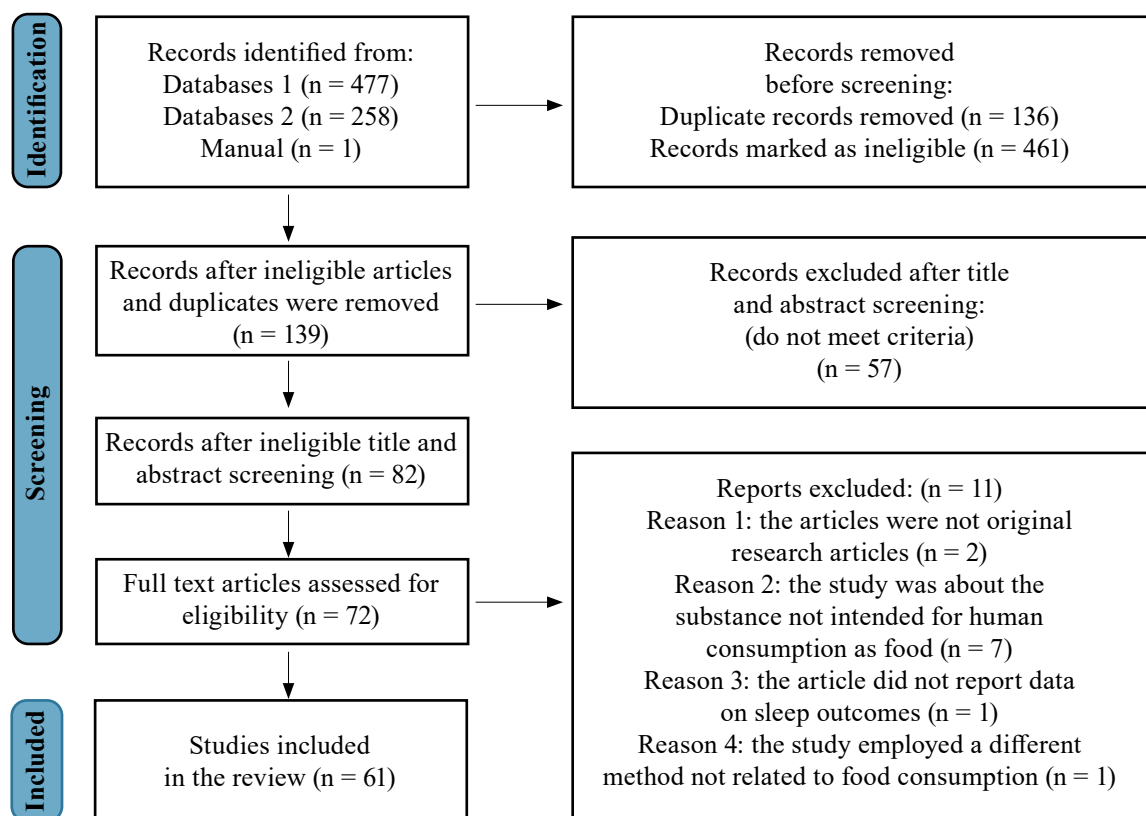


Figure 1 Workflow diagram of the study identification and selection process

Research question. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for systematic scoping reviews was employed as a guideline during the preparation of this review. This approach ensured transparency, rigor, and a structured methodology throughout the review process. Our primary aim was to provide an updated and comprehensive synthesis of evidence addressing the following research question: “How have sleep-related functional foods been studied using electroencephalography?”

Search strategy. To comprehensively address the research question, the study was strategically focused on sensitivity and specificity to identify literature related to food, sleep, and electroencephalography. Three electronic databases – Scopus, PubMed, and Google Scholar – were utilized, with the search conducted by two independent reviewers (A. Sattayakhom & P. Koomhin) on October 30, 2024. The search strategy was “food*” + “electroencephalograph*” + “sleep” or “food” + “electroencephalography” + “sleep”. The search was limited to the articles published until 2024. After the initial acquisition, the studies were further screened. EndNote 20 (PDFNet SDK © PDFTron™ Systems Inc., 2001–2020, distributed by Clarivate Analytics (US) LLC under license) was used for importing and managing the references.

Study selection. To ensure data integrity, EndNote was employed for the identification and removal of duplicate studies. Two reviewers (A. Sattayakhom & P. Koomhin) independently checked the titles for eligibility. Then, three reviewers (A. Sattayakhom, P. Koomhin, and N. Matan) independently assessed the titles and abstracts of all the studies, applying the predetermined inclusion and exclusion criteria. Full texts of the selected studies were then retrieved and thoroughly reviewed. We included original research articles investigating the effects of functional foods on sleep, regardless of electroencephalography use. The articles excluded were those which studied substances not intended for human consumption, lacked sleep-related outcomes, or did not utilize electroencephalography. Disagreements during the selection process were resolved through discussions and mutual agreement among the three reviewers.

Data charting process. Three reviewers (A. Sattayakhom, P. Koomhin, and N. Matan) independently extracted data using a standardized form in Microsoft Excel, including the author, year, country, substance and food type, subject characteristics, study design, intervention, and outcomes. Disagreements were resolved through discussion and consensus among the reviewers. Tables summarizing the characteristics of included studies were created to present the findings of the selected studies.

RESULTS AND DISCUSSION

General findings and characteristics of the studies.

A total of 61 publications were included in the review. Their analysis showed a strong regional focus in East Asia, with the Republic of Korea and Japan collectively contributing 62.30% of the total research entries. Specifically, the Republic of Korea accounted for 37.70% (23 entries), while

Japan contributed 24.59% (15 entries), underscoring their substantial involvement in food and sleep research utilizing electroencephalography (EEG). The foods reported in the research papers were classified based on their purpose, origin, function, nutritive value, and functional properties. They were then grouped into six categories: essential oils, Chinese herbal medicines, plant and fungi extracts, tea and cocoa, probiotics and prebiotics fermented foods, and food supplements. Our analysis revealed that plant and fungi extracts, as well as Chinese herbal medicines, were the most frequently studied ingredients, collectively accounting for 52.46% of the total research entries, namely 29.51% (18 occurrences) for plant and 22.95% (14 occurrences) for fungi extracts. This highlights a global focus on natural and botanical products, particularly in Korea and Japan. Probiotics and prebiotics fermented foods accounted for 14.75% (9 occurrences), with Japanese research dominating in the field of traditional fermentation techniques. Essential oil compounds made up 13.11% (8 occurrences), with Thailand contributing 75.00% (6 occurrences), showcasing the country's expertise in aromatic and culinary applications. Other categories, including food supplements (9.84%) and tea and cocoa (9.84%) contributed equally to the overall study, representing a blend of niche and generalized contributions.

The studies utilized a diverse array of experimental models, with animal and human subjects accounting for 77.42 and 22.58% of the total research entries, respectively. Among the animal models, commonly used species included Institute's of Cancer Research (ICR) mice, Wistar rats, Sprague-Dawley rats, and C57BL/6N mice. These models were employed to investigate various sleep mechanisms, such as pentobarbital-induced sleep, caffeine-induced insomnia, and both acute and chronic sleep disorders. Human studies were characterized by rigorous methodologies, frequently employing double-blind, placebo-controlled, or randomized crossover designs. These studies encompassed a wide range of demographic groups, including healthy adults, individuals with poor sleep quality, and specific occupational populations. This multifaceted approach highlights the comprehensive scope of research on the effects of sleep-related food products across diverse biological and contextual settings.

Advantages of electroencephalography in analyzing food-related sleep studies. EEG has demonstrated its utility in examining the relationship between food intake and sleep. The studies included in this review predominantly consisted of animal (~ 80%) and human (~ 20%) models. The animal studies were further categorized into those involving normal animals and those with induced sleep disorders. The common inductions of sleep disorders included pentobarbital-induced sleep, caffeine-induced insomnia, and ACTH-induced (stress-induced) sleep disturbances. Animal studies offer some advantages, such as the ability to assess the toxicity of unknown substances and explore underlying mechanisms. Notable examples of such research include the studies on crude extracts of tea, cocoa, plant and fungi extracts, and herbal products (Table 1).

Table 1 Characteristics of EEG studies of food types influencing sleep function

Authors, year	Country	Substance	Subject/model	Intervention	Reference
Essential oils (8 entries)					
Cheaha <i>et al.</i> , 2016	Thailand	Vetiver	Wistar rats (male; 300–350 g, 3 months old)	Vetiver essential oil inhalation for 1 h (inhalation chamber)	[30]
Koomhin <i>et al.</i> , 2020	Thailand	<i>Michelia</i> × <i>alba</i> DC.	Healthy adult subjects (male and female, aged 19–25 y.o., sleep more than 6 h prior to the test day)	Inhalation of 50 µL of undiluted <i>Michelia</i> × <i>alba</i> DC. oil on a filter paper	[24]
Chandhara-kool <i>et al.</i> , 2020	Thailand	Tangerine	Healthy adult subjects (male and female, aged 19–25 y.o., sleep more than 6 h prior to the test day)	Inhalation of 25 µL of essential oil that contains a tangerine essential oil concentration of 1:1,000 dilution (spotted on a filter paper)	[25]
Kwangjai <i>et al.</i> , 2021	Thailand	<i>Citrus reticulata</i> Blanco cv. Sai-Nam-Phueng	Wistar rats (male; adult, 300–350 g)	Inhalation of 200 µL of <i>Citrus reticulata</i> Blanco on cotton wool put on saw dust in the rats' home cage inside a soundproof chamber	[26]
Ko <i>et al.</i> , 2021	Taiwan	<i>Lavandula angustifolia</i> Mill.	Healthy, right-handed volunteers (mean age 22 ± 2 years)	Inhalation of <i>Lavandula angustifolia</i> Mill. essential oil repeatedly released starting from 1.5 h after bedtime to 1.5 h before the waking	[27]
Zhou <i>et al.</i> , 2023	China	Anshen essential oil (tangerine peel, rose, atracylodes, lavender, etc.)	ICR mice (male; 6–8 weeks old, 25–35 g); Sprague-Dawley rats (half male and half female; female weight 150–180 g, male weight 200–220 g)/pentobarbital-induced sleep; 10 subjects with poor sleep quality or insomnia (male; aged 20–40 y.o., weight 60–75 kg, height 1.68–1.82 m, without any disease)/self-controlled experiment	The mice sniffed essential oil in an aromatherapy room for 1 h every day for 7 consecutive days; The human subjects were exposed to essential oil from 22:00 on the first night to 7:00 the next morning for 3 consecutive nights	[31]
Cheaha <i>et al.</i> , 2023	Thailand	Jasmine	ICR mice (male; weighing between 25 and 45 g)	Orally administered jasmine oil (10 mL/kg body weight)	[28]
Sinthupachee <i>et al.</i> , 2024	Thailand	Smoke-dried fish hydrolysates with <i>Litsea cubeba</i> (Lour.) Pers. vapor	Twelve non-smoking volunteers (six males and six females) aged 20–45 years	Oral administration: 60 µL of fish protein hydrolysates was placed directly into the subject's mouth and chewed quickly	[29]
Chinese herbal medicine (14 entries)					
Choi <i>et al.</i> , 2014	Republic of Korea	<i>Gastrodiae rhizoma</i>	ICR mice (4 weeks old) and Sprague-Dawley rats (8 weeks old)/pentobarbital-induced sleep	Oral administration (25, 50, and 100 mg/kg)	[40]
Abdollahnejad <i>et al.</i> , 2016	Iran	<i>Amygdalus communis</i> L. (almond)	Wistar rats (male; 250–300 g)/pentobarbital-induced sleep	Intraperitoneal injection of almond extract (100, 200, and 400 mg/kg)	[42]
Yoo <i>et al.</i> , 2017	Republic of Korea	<i>Sinomenium acutum</i> (Thunb.) Rehder & E.H. Wilson	ICR mice (male; 20–25 g, 4 weeks old) and Sprague-Dawley rats (male; 300–320 g, 8 weeks old)/pentobarbital-induced sleep	Oral administration (20 and 40 mg/kg)	[35]
Woo <i>et al.</i> , 2017	Republic of Korea	Decursinol angelate from <i>Angelica gigas</i> Nakai	ICR mice 20–24 g and Sprague-Dawley rats weighing 220–250 g/pentobarbital-induced sleep	Oral administration (10, 25 and 50 mg/kg)	[33]

Continuation of the Table 1

Authors, year	Country	Substance	Subject/model	Intervention	Reference
Wei <i>et al.</i> , 2017	China	Stilbene glucoside from <i>Polygonum multiflorum</i> Thunb.	Kunming mice (three-week old)	Intravenous injection (10, 20, 40, and 80 mg/kg/d)	[32]
Kwon <i>et al.</i> , 2017	Republic of Korea	Rosmarinic acid of <i>Perilla frutescens</i> (L.) Britton	ICR mice 20–24 g and Sprague-Dawley rats weighing 220–250 g/pentobarbital-induced sleep	Oral administration (0.5, 1.0, and 2.0 mg/kg)	[34]
Yoon & Cho, 2018	Republic of Korea	Triphlorethol A found in seaweed (<i>Ecklonia cava</i>)	ICR mice (male, 18–22 g) and C57BL/6N mice (male, 27–30 g)/pentobarbital-induced sleep	Oral administration (50 mg/kg)	[36]
Lin <i>et al.</i> , 2019	China	<i>Pinelliae rhizoma praeparatum cum alumine</i>	SPF C57BL/6J mice 20–25 g (male; 10–12 weeks old)	Intragastric administration (9, 18, and 36 g/kg)	[37]
Yamashiro <i>et al.</i> , 2020	Japan	Polyherbal formulations	Wistar rats (male; 300–450 g, 8–10 weeks old)	Intraperitoneal administration of herbal extract (15 mL/kg)	[43]
Martinez-Mota <i>et al.</i> , 2021	Mexico	<i>Calea zacatechichi</i> Schltdl.	Swiss Webster mice (male; adult, 20–30 g) and Wistar rats (male; adult, 250–300 g)	Oral administration (50, 100, or 1,000 mg/kg, in a constant volume of 10.0 mL/kg for mice, and 2.0 mL/kg for rats)	[44]
Murthy <i>et al.</i> , 2022	India	Ashwagandha (<i>Withania somnifera</i> (L.) Dunal)	Swiss albino mice (male; 25–30 g) and Wistar rats (both sexes; 195–225 g)/pentobarbital-induced sleep	Intraperitoneal administration of a single acute dose of test substances (5, 25, and 50 mg/kg)	[38]
Miyazaki <i>et al.</i> , 2022	Japan	<i>Eurycoma longifolia</i> Jack (<i>Tongkat ali</i>)	C57BL/6N mice (male)	Oral administration: the mice had a diet mixed with extract final ratios of 0.25, 0.5, and 0.75% (w/w)	[39]
Hua <i>et al.</i> , 2022	China	<i>Lonicerae Japonicae</i> Flos extract	C57BL/6J mice (male; 8–12 weeks old, weighting 20–25 g)	Intragastric administration (100 mg/kg)	[41]
Park <i>et al.</i> , 2023	Republic of Korea	Ashwagandha root	ICR mice (male; 28–30 g, 6 weeks old) and Sprague-Dawley rats (male; 180–200 g, 6 weeks old)/caffeine-induced insomnia/pentobarbital-induced sleep	Oral administration (80 mg/kg)	[14]
Plant and fungi extracts (18 entries)					
Yoon <i>et al.</i> , 2014	Republic of Korea	<i>Ecklonia cava</i> ethanol extract	C57BL/6N mice (male; 27–30 g; 12 weeks old)/pentobarbital-induced sleep	Oral administration (100, 250, or 500 mg/kg)	[54]
Yamatsu <i>et al.</i> , 2015	Japan	GABA and AVLE	Sixteen subjects (7 males and 9 females with PSQI scores of 6 or more, average age 36.8 ± 8.9)	Oral administration of gelatin capsules containing GABA (100 mg of GABA and 50 mg of dextrin) or AVLE (50 mg of AVLE and 100 mg of dextrin) or GABA (100 mg) and AVLE (50 mg)	[12]
Uchida <i>et al.</i> , 2016	Japan	Mycelial extract of cultured <i>Cordyceps sinensis</i> extract	Sprague-Dawley rats (male; 250–300 g)	Oral administration of <i>Cordyceps sinensis</i> extract (1 g/kg)	[58]
Abdollahnejad <i>et al.</i> , 2016	Iran	<i>Aloe vera</i> (L.) Burm.f. extract	Wistar rats (male; 250–300 g)/pentobarbital-induced sleep	Intraperitoneal injection of <i>Aloe vera</i> (L.) Burm.f. aqueous extract (50, 100, and 200 mg/kg)	[42]
Kwon <i>et al.</i> , 2017	Republic of Korea	<i>Perillae herba</i> ethanol extract	ICR mice and Sprague-Dawley rats/pentobarbital-induced sleep	Oral administration (12.5, 25, and 50 mg/kg)	[34]
Hong <i>et al.</i> , 2018	Republic of Korea	RE, SE and their mixture	ICR mice (male, 4 weeks) and Sprague-Dawley rats (male, 8 weeks)/pentobarbital-induced sleep	Post-oral injection of RE (80, 100, 120, 140, and 160 mg/kg), SE (40, 50, 80, 100, and 120 mg/kg), and a combination of RE/SE (40, 100, and 120 mg/kg)	[50]

Continuation of the Table 1

Authors, year	Country	Substance	Subject/model	Intervention	Reference
Rahimi <i>et al.</i> , 2019	Iran	Hydroalcoholic taroonch extract (spathe of phoenix dactylifera; a hard-covering envelope of male date palm)	Wistar rats (male; 270 ± 20 g)	Intraperitoneal injection of taroonch extract (62.5, 125, and 250 mg/kg)	[53]
Kim <i>et al.</i> , 2019	Republic of Korea	Green romaine lettuce extract	ICR mice and Sprague-Dawley rats/pentobarbital-induced sleep	Oral administration (80, 100, 120, and 160 mg/kg)	[13]
Takeda <i>et al.</i> , 2020	Japan	Saffron extract	Healthy Japanese adults (male and female; aged 20–64 y.o.)	Oral administration of one tablet (6.6 µg of safranal and 0.66 mg of crocin) per day	[45]
Li <i>et al.</i> , 2021	Taiwan	<i>Hericium erinaceus</i> mycelium	C57BL/6 mice	Oral administration (75 and 150 mg/kg)	[56]
Li <i>et al.</i> , 2021	Taiwan	<i>Armillaria mellea</i> (Fr.) P. Karst. mycelia	Sprague-Dawley rats (male; 8 weeks old, 250–300 g)	Oral administration of <i>Armillaria mellea</i> (Fr.) P. Karst. aqueous and ethanolic extract (75 and 150 mg/kg)	[55]
Kim <i>et al.</i> , 2021	Republic of Korea	Quercetin-3-o-glucuronide in the ethanol extract of lotus leaf	Male ICR mice and Sprague-Dawley rats/pentobarbital-induced sleep/caffeine-induced insomnia model	Oral administration of ethanolic lotus leaf extract (150 [LLE] and 300 [HLE] mg/kg) 1 h before the analysis	[47]
Jo <i>et al.</i> , 2021	Republic of Korea	Green lettuce leaf extract	Drosophila Canton-S strain, Sprague-Dawley rats, and ICR mice (male; 6 weeks old)/pentobarbital-induced sleep	Drosophila was treated with green lettuce leaf extract (0.5 and 1.0%), each concentration added to 5% sucrose and 2% agar media and exposed for nine days. In mice: oral administration (80, 120 mg/kg)	[51]
Kim <i>et al.</i> , 2022	Republic of Korea	<i>Poria cocos</i> (Schw.) Wolf extract	ICR mice (male; 7 weeks old, 20–23 g) and Sprague-Dawley rats (male; 8 weeks old, weighing 180–190 g)/pentobarbital-induced sleep, caffeine-induced sleep disturbance, ACTH-induced sleep disorder	Oral administration of <i>Poria cocos</i> (Schw.) Wolf extract (10, 20, 40, 80, 160, and 320 mg/kg)	[57]
Kim <i>et al.</i> , 2022	Republic of Korea	Green kiwifruit peel ethanol extract	C57BL/6N mice (male; 27–30 g)/pentobarbital-induced sleep	Oral administration of green kiwifruit peel ethanol extract (250, 500, and 1,000 mg/kg/day)	[18]
Ahn <i>et al.</i> , 2022	Republic of Korea	Lotus rhizome extract	ICR mice (male; 5 weeks old, 20 ± 2 g) and Sprague-Dawley rats (male; 8 weeks old, 180 ± 20 g)/pentobarbital-induced sleep	Oral administration of lotus rhizome extract (120 or 150 mg/kg)	[46]
Kim <i>et al.</i> , 2023	Republic of Korea	<i>Chrysanthemum × morifolium</i> var. <i>gracile</i> Hemsl. 50% ethanol extract	ICR mice (male; 32–35 g) and Sprague-Dawley rats (male; 280–300 g)/pentobarbital-induced sleep	Oral administration of <i>Chrysanthemum × morifolium</i> var. <i>gracile</i> Hemsl. 50% ethanol extract (50, 100, and 200 mg/kg)	[17]
Ahn <i>et al.</i> , 2023	Republic of Korea	Heukharang lettuce leaf extract	ICR mice (male; 6 weeks old, 30 g) and Sprague-Dawley rats (male; 5 weeks old, 130 g)/pentobarbital-induced sleep	Oral administration of Heukharang lettuce leaf extract (50, 80, 100, and 150 mg/kg)	[49]
Tea and cocoa (6 entries)					
Panagiotou <i>et al.</i> , 2019	The Netherlands	Caffeine	C57BL/6JOLA Hsd mice (male; 12 weeks old)	Oral administration of 6 mL per day of caffeine containing water (0.8 mg/mL caffeine (0.08%))	[59]
Kwon <i>et al.</i> , 2019	Republic of Korea	Phlorotannin (brown seaweed polyphenol) supplement	C57BL/6N (male, 27–30 g, 11 weeks old)/caffeine-induced sleep disruption	Oral administration of phlorotannin supplement (500 mg/kg)	[61]

Continuation of the Table 1

Authors, year	Country	Substance	Subject/model	Intervention	Reference
Kim <i>et al.</i> , 2019	Republic of Korea	GABA and L-theanine	ICR mice (male; 4 weeks old, 18–20 g) and Sprague-Dawley rats (male; 8 weeks old, 160–180 g)/pentobarbital-induced sleep	Oral administration of GABA (60, 80, and 100 mg/kg), L-theanine (20, 30, and 40 mg/kg), or both (GABA/L-theanine) (80/20, 80/30, 100/20, and 100/30 mg/kg)	[13]
Oishi <i>et al.</i> , 2020	Japan	Natural cocoa seed powder	C3 H/HeN mice (male; 5 weeks old)/chronic sleep disorders model	Dietary cocoa consumption (containing 2.0% natural cocoa)	[62]
Kim <i>et al.</i> , 2023	Republic of Korea	Green tea ethanol extract and caffeine	C57BL/6N mice (11 weeks old)	Oral administration of green tea ethanol extract (1,500 mg/kg) and caffeine (25 mg/kg)	[60]
Baba <i>et al.</i> , 2023	Japan	L-theanine	University students (female; aged 21.3 ± 0.5 , BMI 21.6 ± 2.2)/a single-dose, four-treatment double-blind, crossover design	Oral administration of drinks containing caffeine (30 mg), theanine (50 mg), or both; caffeine and theanine were mixed in 200 mL of deionized water, adjusted to have the same taste and aroma as placebo drinks and dispensed in cans of the same shape	[22]
Probiotics and prebiotics fermented foods (9 entries)					
Miyazaki <i>et al.</i> , 2014	Japan	Heat-killed <i>Lactobacillus brevis</i> SBC8803	C3H-HeN mice (male; 6 weeks old)/pentobarbital-induced sleep	Oral administration of a diet supplemented with 0.5% heat-killed SBC8803	[63]
Nakamura <i>et al.</i> , 2016	Japan	Japanese sake yeast (<i>Saccharomyces cerevisiae</i> sake)	C57BL/6N strain mice (male; 23–27 g, 8 weeks old)	Oral administration of sake yeast (100, 200, and 300 mg/kg)	[15]
Monoi <i>et al.</i> , 2016	Japan	Sake yeast	68 Japanese volunteers (weekday full-time employees; 35 female and 33 male; aged 38.2 ± 1.1 years, with PSQI scores > 6 (averaging 6.8 ± 0.2))	Oral administration of 4 tablets (125 mg sake yeast powder per tablet) per day for 4 days 1 h before bedtime	[66]
Yamatsu <i>et al.</i> , 2015	Japan	GABA	10 Japanese volunteers (6 male and 4 female; average age: 37.7 ± 11.5 years, age range: 24–57 years; with PSQI scores of 6 or more)	Oral administration of 100 mg GABA in a gelatin capsule	[12]
Thompson <i>et al.</i> , 2017	USA	Prebiotics (galactooligosaccharides and polydextrose), lactoferrin, and milk fat globule membrane	F344 rats (adult males; 40–50 g at arrival, post-natal day 24)	Oral administration of a diet supplemented with prebiotics, lactoferrin, and milk fat globule membrane for four weeks	[64]
Nakagawa <i>et al.</i> , 2018	Japan	Lactic acid bacteria-containing food (900 mg of fermented products of LBH_MIKI-020, 200 mg of live lactic acid bacteria powder, 200 mg of ground lactic acid bacteria powder, and 200 mg of theanine in a daily amount)	Men and women aged 20–64 years who have a problem with everyday sleep/a placebo-controlled, double-blinded, randomized crossover study	Oral administration of 8 tablets (total 4.8 g) of the lactic acid bacteria-containing food daily	[23]
Higo-Yamamoto <i>et al.</i> , 2019	Japan	Heat-killed <i>Lactobacillus brevis</i> SBC8803	C3H/HeN mice (male; 5 weeks old)	Oral administration of a diet supplemented with 0.5% heat-killed SBC8803 for 6 weeks	[65]
Nedachi <i>et al.</i> , 2021	Japan	Lactic-fermented barley GABA, lafma extract, vitamin B ₁₂ , and vitamin B ₆	Healthy middle-aged females (40–64 years after menopause with lower sleep quality)/randomized, double-blind, placebo-controlled, parallel intergroup comparison study	Oral administration, with water, 30–60 min before sleep, with no chewing, for 4 weeks (main ingredients: lactic-fermented barley GABA (120 mg), lafma extract (50 mg), 0.1% vitamin B ₁₂ (3 mg), and vitamin B ₆ (1.5 mg))	[75]

Continuation of the Table 1

Authors, year	Country	Substance	Subject/model	Intervention	Reference
Bac <i>et al.</i> , 2023	Republic of Korea	ZW, ZW-AT, ZW-EH, and ZW-FM	ICR mice (male; 5 weeks old, 25–27 g)/pentobarbital-induced sleep	Oral administration of ZW (150 and 200 mg/kg), ZW-AT (150 and 200 mg/kg), ZW-EH (150 and 200 mg/kg), and ZW-FM (50, 80, 100, 150, and 200 mg/kg)	[68]
Food supplements (6 entries)					
Minet-Ringuet <i>et al.</i> , 2004	France	Dietary regimens varying in terms of the protein amount (14 versus 30%) or quality (milk protein or alpha-lactalbumin)	Wistar rats (male)	Oral administration with diet (3 regimens: P14 (140 g/kg whole milk protein), P30-WMP (300 g/kg whole milk protein), and P30-LAC (P30 + alpha-lactalbumin > 40%))	[69]
Ta <i>et al.</i> , 2015	Republic of Korea	Blue mussel water extracts	ICR mice (male, 18–22 g)/pentobarbital-induced sleep	Oral administration (125, 250, 500, 1,000 and 1,500 mg/kg)	[74]
Cherasse <i>et al.</i> , 2015	Japan	Zinc-containing yeast extract	C57BL/6 strain mice (male; 23–27 g, 11–13 weeks old)	Oral administration of zinc-containing yeast extract (40 and 80 mg/kg/10 mL/kg)	[72]
Halsen <i>et al.</i> , 2020	Australia	Tart cherry juice, high GI CHO, α -lactalbumin, adenosine-5-monophosphate, valerian, and theanine	Healthy males (age: 27.4 ± 6.2 years; weight: 83.2 ± 11.5 kg; height: 181.2 ± 6.7 cm)/double-blind, placebo-controlled cross-over experimental design	Oral administration of a dietary supplement (a combination of tart cherry juice (0, 50, 100 mL), high GI CHO (0, 25, 50 g), α -lactalbumin (0, 20, 40 g), adenosine-5-monophosphate (0, 26.5, 53 mcg), valerian (0, 750, 1,500 mg), and theanine (0, 500, 1,000 mg))	[70]
Thiagarajah <i>et al.</i> , 2022	Malaysia	α -s1-casein tryptic hydrolysate and L-theanine	Human subjects (aged 37.3 ± 8.4 years)	Oral administration of a supplement containing 150 mg α -s1-casein tryptic hydrolysate and 50 mg L-theanine in the same capsule	[71]
Ye <i>et al.</i> , 2023	Republic of Korea	<i>Glycine max</i> (L.) Merr. extract and genistein	Sprague-Dawley rats (8 weeks old)/pentobarbital-induced sleep	Oral administration of <i>Glycine max</i> (L.) Merr. extract (400 mg/kg) and genistein (30 mg/kg)	[73]

ICR – Institute of Cancer Research; GABA – γ -aminobutyric acid; AVLE – *Apocynum venetum* L. leaf extract; PSQI – Pittsburgh Sleep Quality Index; RE – romaine lettuce leaves extract; SE – skullcap root extract; ZW – jujube seed water extract; ZW-AT – jujube seed water extract – alcohol treated; ZW-EH – jujube seed water extract – enzyme hydrolysate; ZW-FM – jujube seed water extract – fermented product

Sleep disorder models are used to examine differences in sleep physiology and mechanisms between normal and disrupted sleep. In clinical settings, various pharmacological treatments, such as barbiturates, are prescribed to patients with sleep disorders. Therefore, identifying adjunctive therapies that enhance the efficacy of these treatments is crucial. For disorders such as caffeine-induced or stress-induced sleep disturbances, interventions tailored to the specific disorder are more effective.

Human studies involve both healthy individuals and those with poor sleep quality. While animal studies commonly employ invasive EEG and electromyography (EMG) with implanted electrodes, human studies typically rely on non-invasive methods. Quantitative sleep staging analysis is often conducted using either manual or automated scoring systems. Certain software can analyze sleep stages, such as wakefulness, slow-wave

sleep (SWS) and rapid eye movement (REM), without the need for EMG data. However, some methods require EMG signals from the nuchal muscles to distinguish between wakefulness and REM sleep. Both qualitative and quantitative assessments are commonly used in human studies, with the Pittsburgh Sleep Quality Index frequently utilized for qualitative evaluation.

Sleep parameters typically measured in these studies include wakefulness, sleep latency, REM latency, wake time after sleep onset, total sleep time, time spent in bed, and sleep efficiency [7]. Noteworthy, the definitions of these parameters may vary between the studies, as presented in Table 2. Although we adopted a simplified approach to categorizing sleep parameters to facilitate screening across the studies, experimental details should be carefully considered when interpreting the results.

Table 2 Primary objective sleep outcomes

Author, year	Intervention	Species	Outcomes	References
Minet-Ringuet <i>et al.</i> , 2004	Tryptophan-rich protein diet	Rats	– increased SWS	[69]
Choi <i>et al.</i> , 2014	<i>Gastrodiae rhizoma</i> ethanol extract	Mice	– shortened sleep latency – increased total sleep time – decreased sleep/wake cycles	[40]
Yoon <i>et al.</i> , 2014	<i>Ecklonia cava</i>	Mice	– increased SWS	[54]
Miyazaki <i>et al.</i> , 2014	Dietary heat-killed <i>Lactobacillus brevis</i> SBC8803	Mice	– reduced wakefulness – increased SWS	[63]
Yamatsu <i>et al.</i> , 2015	– Oral GABA – <i>Apocynum venetum</i> L. leaf extract	Human	– shortened sleep latency – increased SWS	[12]
Ta <i>et al.</i> , 2015	Blue mussel water extracts	Mice	– shortened sleep latency – increased SWS – increased total sleep time	[74]
Cherasse <i>et al.</i> , 2015	Zinc-containing yeast extract	Mice	– increased SWS	[72]
Yamatsu <i>et al.</i> , 2015	Oral GABA	Human	– shortened sleep latency – increased SWS	[12]
Uchida <i>et al.</i> , 2016	Mycelial extract of cultured <i>Cordyceps sinensis</i>	Rats	– reduced wake after sleep onset – increased SWS	[58]
Nakamura <i>et al.</i> , 2016	Japanese sake yeast	Mice	– increased SWS	[15]
Mono <i>et al.</i> , 2016	Japanese sake yeast	Human	– increased delta wave power	[66]
Cheaha <i>et al.</i> , 2016	Vetiver essential oil inhalation	Rats	– increased waking period – reduced SWS	[30]
Abdollahnejad <i>et al.</i> , 2016	<i>Aloe vera</i> (L.) Burm.f. aqueous extract	Rats	– increased SWS – decreased REM – increased total sleeping time	[42]
Abdollahnejad <i>et al.</i> , 2016	<i>Amygdalus communis</i> L. extract	Rats	– increased total sleep time – increased sleep/wake cycles	[42]
Yoo <i>et al.</i> , 2017	Sinomenine	Mice	– shortened sleep latency – increased total sleep time	[35]
Woo <i>et al.</i> , 2017	Decursinol angelate	Mice	– increased total sleep time – decreased sleep/wake cycles	[33]
Wei <i>et al.</i> , 2017	Stilbene Glucoside (<i>Polygonum multiflorum</i> Thunb.)	Mice	– reduced wake after sleep onset – increased SWS – reduced REM – increased total sleep time	[32]
Thompson <i>et al.</i> , 2017	Dietary prebiotics and bioactive milk fractions	Rats	– increased SWS	[64]
Kwon <i>et al.</i> , 2017	Rosmarinic acid	Mice	– shortened sleep latency – increased total sleep time – increased number of falling asleep	[34]
Kwon <i>et al.</i> , 2017	Ethanol extract of <i>Perillae herba</i>	Mice	– increased SWS – increased total sleep time – decreased sleep/wake cycles	[48]
Yoon & Cho, 2018	Triphlorethol A	Mice	– shortened sleep latency – increase total sleep time	[36]
Nakagawa <i>et al.</i> , 2018	Lactic acid bacteria-containing foods	Human	– increase total sleep time	[23]
Hong <i>et al.</i> , 2018	Romaine lettuce/skullcap mixture	Mice	– increased SWS – increase total sleep time	[50]
Rahimi <i>et al.</i> , 2019	Hydroalcoholic taroonch extract	Rats	– increased delta wave power – decreased alpha and beta wave power – increased total sleep time	[53]
Panagiotou <i>et al.</i> , 2019	Chronic caffeine consumption	Mice	– increased SWS	[59]
Lin <i>et al.</i> , 2019	<i>Pinelliae Rhizoma Praeparatum Cum Alumine</i> extract	Mice	– reduced wakefulness – increased SWS – increased REM	[37]
Kwon <i>et al.</i> , 2019	A standardized phlorotannin supplement	Mice	– increased sleep latency – decreased SWS	[61]

Continuation of the Table 2

Author, year	Intervention	Species	Outcomes	References
Kim <i>et al.</i> , 2019	GABA and L-theanine mixture	Mice	– shortened sleep latency – increase total sleep time	[13]
Kim <i>et al.</i> , 2019	Green Romaine lettuce (<i>Lactuca sativa</i> L.)	Rats	– increased SWS – reduced REM	[52]
Higo-Yamamoto <i>et al.</i> , 2019	Dietary heat-killed <i>Lactobacillus brevis</i> SBC8803	Mice	– increased SWS – reduced REM	[65]
Yamashiro <i>et al.</i> , 2020	Polyherbal formulation	Rats	– reduced total sleep time	[43]
Koomhin <i>et al.</i> , 2020	Michelia essential oil	Human	– reduced wakefulness	[24]
Takeda <i>et al.</i> , 2020	Saffron-derived Crocin and Safranal	Human	– shortened sleep latency – increased SWS – reduced wake after sleep onset	[45]
Oishi <i>et al.</i> , 2020	Dietary natural cocoa	Mice	– increased SWS	[62]
Chandharakool <i>et al.</i> , 2020	Tangerine essential oil	Human	– shortened sleep latency	[25]
Halsen <i>et al.</i> , 2020	Nutritional intervention	Human	– shortened sleep latency	[70]
Martinez-Mota <i>et al.</i> , 2021	<i>Calea zacatechichi</i> Schltdl. (Compositae)	Rats	– increased SWS	[44]
Nedachi <i>et al.</i> , 2021	GABA and lafma	Human	– increased delta power	[75]
Kim <i>et al.</i> , 2021	Quercetin-3-O-glucuronide in the ethanol extract of lotus leaf	Mice	– increased SWS – reduced REM – increased total sleep time	[47]
Jo <i>et al.</i> , 2021	Green lettuce leaf extract	Rats	– increased SWS – reduced REM – increased total sleep time	[51]
Li <i>et al.</i> , 2021	<i>Armillaria mellea</i> (Fr.) P. Karst. mycelia	Rats	– increased SWS – increased REM	[55]
Kwangjai <i>et al.</i> , 2021	<i>Citrus reticulata</i> Blanco. cv. Sai-Nam-Phueng essential oil	Rats	– shortened REM sleep latency – increased REM sleep time – increased SWS and REM episodes	[26]
Li <i>et al.</i> , 2021	<i>Hericium erinaceus</i> mycelium	Mice	– increased SWS – reduced REM	[56]
Ko <i>et al.</i> , 2021	Essential oil aroma (lavender aroma)	Human	– increased delta wave power	[27]
Thiagarajah <i>et al.</i> , 2022	Alpha-S1-casein tryptic hydrolysate and L-theanine	Human	– increased total sleep time	[71]
Kim <i>et al.</i> , 2022	Green kiwifruit peel extract	Mice	– shortened sleep latency – increased SWS	[18]
Hua <i>et al.</i> , 2022	<i>Lonicerae Japonicae</i> Flos extract	Mice	– shortened sleep latency – increased SWS – increased REM	[41]
Murthy <i>et al.</i> , 2022	Hydroalcoholic extract of ashwagandha	Rats	– shortened sleep latency – increased total sleep time	[38]
Ahn <i>et al.</i> , 2022	Lotus (<i>Nelumbo nucifera</i> Gaertn.) rhizome water extract	Mice	– increased SWS – increased total sleep time – increased theta and delta wave powers	[46]
Miyazaki <i>et al.</i> , 2022	<i>Eurycoma longifolia</i> Jack extract	Mice	– increased SWS – increased REM – increased delta wave power – reduced wakefulness during the dark period	[39]
Kim <i>et al.</i> , 2022	<i>Poria cocos</i> (Schw.) Wolf extract	Mice	– shortened sleep latency – increased SWS – increased total sleep time	[57]
Cheaha <i>et al.</i> , 2023	Jasmine essential oil	Mice	– reduced wake after sleep onset – increased SWS	[28]
Ahn <i>et al.</i> , 2023	Heukharang lettuce (<i>Lactuca sativa</i> L.) leaf extract	Mice	– reduced wake after sleep onset – increased SWS – increased REM – increased delta wave power – increased total sleep time	[49]

Continuation of the Table 2

Author, year	Intervention	Species	Outcomes	References
Ye <i>et al.</i> , 2023	<i>Glycine max</i> (L.) Merr. extract (functional food)	Rats	– reduced awakening time – increased SWS – increased REM	[73]
Bae <i>et al.</i> , 2023	Water extract from Jujube (<i>Zizyphus jujuba</i> Mill.) seeds	Mice	– shortened sleep latency – increased SWS – increased delta wave power – increased total sleep time	[68]
Kim <i>et al.</i> , 2023	Green tea ethanol extract	Mice	– increased sleep latency – increased wakefulness	[60]
Baba <i>et al.</i> , 2023	Theanine (non-proteinogenic amino acid found in the leaves of <i>Camellia sinensis</i> (L.) Kuntze)	Human	– reduced wake after sleep onset	[22]
Kim <i>et al.</i> , 2023	<i>Chrysanthemum</i> × <i>morifolium</i> var. <i>gracile</i> Hemsl.	Mice	– increased SWS – reduced wake after sleep onset – increased delta wave power – increased total sleep time	[17]
Park <i>et al.</i> , 2023	Ashwagandha (<i>Withania somnifera</i> L. Dunal) root extract	Mice and Rats	– reduced wake after sleep onset – increased SWS – increased delta wave power – increased total sleep time	[14]
Zhou <i>et al.</i> , 2023	Anshen essential oil	Mice	– shortened sleep latency – increased total sleep time	[31]

SWS – slow-wave sleep; REM – rapid eye movement; GABA – γ -aminobutyric acid

The sleep-wake system is a complex, interconnected network of wake-promoting and sleep-promoting centers in the brain. Orexinergic neurons are central to regulating arousal and maintaining wakefulness, receiving input from multiple brain regions, including the brainstem, basal forebrain, prefrontal cortex, and hypothalamus [8, 9]. The ventrolateral preoptic nucleus (VLPO) plays a pivotal role in sleep induction and maintenance, with GABAergic neurons projecting to, and inhibiting, wake-promoting centers and thereby facilitating the onset of sleep [10]. According to the circadian rhythm model, the suprachiasmatic nucleus (SCN) sends signals to the VLPO indirectly during the nighttime period to initiate sleep. This sleep-promoting signal is further enhanced by melatonin released from the pineal gland, which increases the SCN's sensitivity to its own sleep-inducing signals [11]. The VLPO is inhibited by wake-promoting neurotransmitters, such as noradrenaline.

The studies examining the effects of foods and beverages on sleep parameters often focus on neurotransmitter systems [12–15], such as the GABAergic, adrenergic, glutamatergic, and serotonergic systems, as well as peripheral neural networks. The GABAergic system is frequently studied as a target. While the central nervous system is often the primary focus, the peripheral nervous system also provides valuable insights into sleep-wake physiology. GABAergic neurons play a crucial role in the mechanism of action of sedative-hypnotic drugs, such as barbiturates, which increase chloride conductance within GABAergic neurons [16].

Recent years have seen a growing interest in the development of natural sleep aids to mitigate the adverse effects of standard pharmacological treatments [17, 18]. While no single drug can perfectly replicate the physiological sleep-wake cycle, combining treatments that extend the benefits

of sedative-hypnotic drugs, particularly during the SWS and REM stages, holds promising therapeutic potential. Although there is no evidence that oral γ -aminobutyric acid (GABA) supplementation crosses the blood-brain barrier, studies suggest that GABA intake can reduce stress and anxiety, promote relaxation, and stimulate the parasympathetic nervous system and enteric nervous system [19]. As such, GABA is considered a key ingredient in functional foods aimed at enhancing sleep. Several substances can increase central GABA levels by upregulating glutamic acid decarboxylase, benefiting both central and peripheral mechanisms [12, 17].

Another key neurotransmitter system involved in sleep regulation is the adrenergic system. Following prolonged wakefulness, adenosine triphosphate is metabolized into adenosine, which, at high levels, stimulates the adenosine A_{2A} receptor, promoting sleep onset in accordance with the homeostatic theory of sleep [20]. Caffeine blocks this receptor, thus increasing alertness. Consequently, compounds that stimulate this receptor represent potential targets for sleep-promoting agents [21].

The glutamatergic system remains less studied, but emerging evidence suggests that L-theanine may act as an antagonist at the α -amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid receptor, potentially influencing sleep regulation [22]. Serotonergic neurotransmitters also play a role in stress responses and the maintenance of the GABAergic system, contributing to sleep rhythm regulation in some individuals. Additionally, several peripheral targets, such as the peroxisome proliferator-activated receptor alpha and the gut microbiota, have been implicated in the modulation of sleep physiology, offering further avenues for therapeutic intervention [23].

Types of foods related to sleep based on electroencephalography results. The classification of foods related to sleep is based on EEG data, which includes their purpose, origin, function, nutritive value, and functional properties. Foods are categorized into six types: essential oils, Chinese herbal medicines, plant and fungi extracts, tea and cocoa, probiotics and prebiotics from fermented foods, and food supplements.

Essential oils. Essential oils with distinct fragrances are widely used as food flavor ingredients due to their diverse properties. Their aroma often reflects the raw materials from which they are derived and thereby contributes to acceptable flavors in various food products. Numerous studies have shown that essential oils can influence human sleep by modulating alpha, beta, delta, and theta waves (Table 1). For example, *Michelia × alba* DC. oil reduced wakefulness and increased alpha fast activity, indicating sleep-enhancing effects [24]. Tangerine oil also reduced alpha and beta waves while increasing theta wave power, promoting relaxation and reducing sleep onset latency [25]. Orange oil, containing 75% of d-limonene, significantly increased the frequency and duration of REM sleep, while decreasing sleep onset latency and overall sleep duration [26]. Lavender oil promoted SWS by decreasing alpha wave activity and increasing delta wave activity [27]. Jasmine oil, which influences brain regions responsible for stress and anxiety, induced slow delta and beta oscillations, supporting non-rapid eye movement (NREM) sleep and suggesting its potential as a treatment for anxiety and insomnia [28]. Additionally, *Litsea cubeba* (Lour.) Pers. vapor altered brain waves differently in male and female participants, promoting relaxation in the males and causing heightened alertness in the females [29].

Essential oils extracted from various plant parts, though typically less fragrant than those from specific raw materials, can still significantly impact sleep when inhaled or ingested. For example, *Vetiveria zizanoides* (L.) Nash, an aromatic grass from tropical regions, can stimulate alertness and enhance task performance. Exposure to this oil was associated with REM sleep and a dominant parietal theta wave, with high electromyography activity during wakefulness and its near-absence during REM sleep [30]. Additionally, the key components of *Anshen* essential oil, including (+)-limonene, linalool, and ocimene, were shown to improve sleep duration and increase neurotransmitter levels, such as 5-hydroxytryptamine and GABA, in mice with induced insomnia [31].

Chinese herbal medicine. Chinese herbal medicine (CHM), which is often incorporated into traditional food dishes and herbal products (Table 1), has long been used to treat various diseases and manage insomnia. Typically made from herbs and spices, CHM is prepared as powders or water-based extracts. Recent studies using EEG techniques have provided valuable insights into the effects of CHM on sleep. While most CHM materials are traditionally sourced from Asian countries (primarily China, Republic of Korea, Japan, India, and Iran), similar active compounds from other regions

are also utilized. This has supported the development of sleep-promoting products in various countries, including Mexico. Notable CHMs for insomnia include *Polygonum multiflorum* Thunb., which contains stilbene glucoside to improve sleep by reducing wakefulness and REM sleep while enhancing NREM sleep [32]; *Sinomenium acutum* (Thunb.) Rehder & E.H. Wilson, which activates the GABAergic system to improve NREM sleep [33]; and *Perilla frutescens* (L.) Britton, with rosmarinic acid that similarly boosts NREM sleep via the GABAergic system [34]. Traditional remedies such as *Angelica dahurica* (Hoffm.) Benth. & Hook.f. ex Franch. & Sav. (Bai Zhi) stimulate GABA_A receptors, aiding in insomnia relief [35], while brown seaweed extract interacts with GABA_A receptors to promote sleep [36]. Additionally, *Pinellia ternata* (Thunb.) Makino enhances both REM and NREM sleep, reducing wakefulness and sleep interruptions [37].

Extracts from *Withania somnifera* (L.) Dunal (ashwagandha) have shown potential for improving sleep by enhancing brainwave activity, including delta waves. They also support NREM and slow-wave sleep cycles, helping calm the mind and improve sleep quality [14, 38]. Similarly, *Eurycoma longifolia* Jack (*Tongkat ali*) has been found to improve sleep rhythms and increase delta power during NREM sleep, possibly through body temperature regulation, suggesting its potential as a natural remedy for sleep problems [39]. *Gastrodiae rhizoma* extract has also demonstrated sleep benefits by reducing sleep onset time, increasing total sleep duration, and enhancing REM sleep structure [40]. Flower-based extracts used in CHM, such as *Lonicerae Japonicae Flos* (honeysuckle), have been shown to improve sleep by reducing sleep onset time and increasing REM sleep during recovery from sleep deprivation [41]. *Aloe vera* (L.) Burm.f. extract has been reported to positively affect both REM and NREM sleep, extending total sleep time and inducing calming effects [42]. Additionally, *Amygdalus communis* L. (almond extract) enhances sleep duration and NREM sleep, while traditional herbal combinations, such as linden, mulberry, lavandin, butterfly pea, and tulsi, have been studied for their ability to reduce sleep latency and improve sleep quality [43]. Similarly, *Calea zacatechichi* Schltdl., traditionally used in Mexico, exhibits anxiolytic-like effects and promotes sleep stages associated with memory consolidation [44]. These findings highlight the potential of flower- and food-based CHMs as natural alternatives for managing sleep issues.

Plant and fungi extracts. Plant extracts, derived from fruits, roots, flowers, stems, and leaves, contain active compounds and are increasingly used as functional ingredients in food. Mushroom extracts, valued for their flavor in human diets and medicinal properties, have gained attention for improving sleep quality, particularly in oriental countries. This highlights the potential of natural ingredients in promoting better sleep and overall well-being.

Among plant extracts, saffron, derived from the flower of *Crocus sativus* Herb., has demonstrated promising effects on sleep quality by reducing sleep onset time and nighttime awakenings while increasing NREM sleep. These benefits are attributed to its active compounds, crocin and safranal, which enhance sleep quality and rhythm [45]. The ethanol extract of lotus leaf (*Nelumbo nucifera* Gaertn.), particularly quercetin-3-O-glucuronide, improves sleep by interacting with GABA_A receptors, enhancing both sleep quantity and quality [46, 47]. Chrysanthemum extract and its active compound linarin have also shown potential by increasing sleep duration in animal models [17].

Promising sleep benefits are also offered by the plant extracts derived from food by-products, such as kiwifruit peel, lettuce leaves, and aloe vera [42]. Kiwifruit peel ethanol extract increases NREM sleep and reduces sleep latency in a dose-dependent manner [18]. *Perillan herba* and *Heukharang* lettuce (*Lactuca sativa* L.) extracts enhance NREM sleep by interacting with GABA_A-BZD receptors [48]. Additionally, GABA supplementation at a dose of 100 mg has been reported to reduce sleep onset by 5.3 min and improve sleep quality [12]. Green lettuce extract (100 mg/kg) increased total sleep time and improved NREM sleep in animal studies, with *Heukharang* lettuce demonstrating similar effects [49–52]. Date palm extract (125 mg/kg) has been found to improve sleep by increasing delta waves and reducing alpha and beta waves, thus contributing to deep, restful sleep [53]. Additionally, seaweed extracts, such as *Ecklonia cava* ethanol extract, induce NREM sleep without affecting REM sleep, promoting natural physiological sleep [54].

Fungi extracts have also shown promise in managing sleep disorders. *Hericium erinaceus* (honey mushroom) mycelium contains erinacine, which supports nervous system functions and improves both NREM and REM sleep, reducing anxiety and insomnia [55, 56]. *Poria cocos* (Schw.) Wolf (Bokryeong), a sclerotium fungus, enhances slow-wave sleep, reduces sleep latency, and improves sleep structure by activating GABA_A receptors [57]. *Cordyceps sinensis* (Dong Chong Xia Cao) extract alleviated stress-induced sleep disturbances in rats by improving their stress adaptability and sleep restoration within hours [58]. These findings underscore the potential of plant and fungi extracts as natural remedies for improving sleep quality and offering both calming and restorative effects.

Tea and cocoa. Caffeine is one of the most commonly used stimulants in daily life. People consume caffeine through drinks such as coffee and tea. It affects sleep and our internal body clock. Chronic caffeine consumption leads to increased sleep pressure, meaning the body becomes more in need of sleep over time. However, chronic caffeine use can also make some people stay awake longer. In recent years, more people are staying awake to make up for lack of sleep (Table 1). In studies, caffeine has been shown to have different effects depending on how often it is consumed. In the

short term, caffeine can make people stay awake, but when consumed long-term, it may increase the body's daily sleep-wake cycle. This means that people may sleep more during the light period and stay awake more during the dark period [59].

Green tea (*Camellia sinensis* (L.) Kuntze) also contains caffeine, like coffee. However, green tea has a relaxing effect due to an amino acid called theanine. Theanine can reduce caffeine's effects on sleep quality [22]. This suggests that drinking green tea may help improve sleep, especially in people who consume a lot of caffeinated beverages [60]. Green tea also contains GABA, an important neurotransmitter that promotes relaxation and sleep. When GABA is combined with theanine, it can improve sleep quality, as shown in studies with mice [13]. Additionally, phlorotannins, a type of polyphenol found in brown seaweed, can promote sleep by affecting the GABA_A receptors. This may help relieve temporary insomnia caused by caffeine consumption [61].

Cacao beans, used in making chocolate and cocoa, are rich in phenolic compounds that may help prevent diseases related to inflammation and stress. Flavonoids in cocoa also have benefits for the brain, improving mood, memory, and learning by activating nitric oxide in blood vessels. Regular consumption of cocoa can help reduce sleep problems caused by stress without affecting sleep patterns under normal conditions [62]. In summary, both green tea and cocoa offer benefits for sleep improvement, with the ability to reduce the negative effects of caffeine and promote relaxation.

Probiotics, prebiotics, and fermented foods. Fermented foods contain probiotic bacteria, such as *Lactobacillus* species, which are commonly used as supplements to improve health, especially by supporting the immune system. Changes in the gut microbiome are linked to sleep patterns in both humans and animals (Table 1). These changes can enhance REM sleep but may also result in poorer overall sleep quality. Additionally, certain peptides from the digestion of protein and the cell walls of intestinal bacteria can enhance NREM sleep. This suggests that sleep and gut health are connected and may influence each other [63]. In a study with men and women aged 20–64, those who had trouble sleeping and took lactic acid bacteria supplements showed improvements in sleep quality. The study, which was placebo-controlled and randomized, suggests that probiotics may be a safe way to improve sleep quality for people dealing with sleep issues [23]. The gut-brain axis refers to the interaction between the brain and the intestines, and food components can influence this system through the gut microbiome. Probiotics, such as *Lactobacillus gasseri*, can interact with the gut environment and provide health benefits, including better sleep quality.

In addition, prebiotic diets, rich in prebiotics and glycoproteins, can influence the gut microbiota and promote the growth of microbial species that help reduce the impact of stress. For example, a diet rich in prebiotics can regulate the sleep and wake cycle both before

and after stress and provide stress-protective effects on daily physiology and the gut microbiota. Consumption of a prebiotic-rich diet has been shown to improve early-life NREM sleep and enhance REM sleep rebound following stress [64]. Fiber mixed with *Lactobacillus brevis* significantly helps restore wakefulness and increases NREM sleep. During the early stages of the inactive period, NREM sleep was significantly improved by the consumption of prebiotics [65].

Many fermented foods are made using probiotics. The use of yeast fermentation, such as in sake or Japanese rice wine, helps promote NREM sleep by activating receptors, which makes it a potential candidate for a supplement to improve sleep quality [15]. This is consistent with reports that drinking sake offers benefits without any adverse effects, with sake yeast supplementation being an effective and safe way to support high-quality, deep sleep [66]. In fermented foods, glucose obtained from the fermentation of starch or from high-glucose beverages contributes to facilitating sleep onset by increasing the excitability of sleep-promoting neurons in the ventrolateral preoptic nucleus. Glucose-induced excitation of the VLPO is thought to be involved in the drowsiness experienced after consuming a high-sugar meal. This new mechanism regulating VLPO neuron activity highlights the close connection between sleep and metabolism [67].

During fermentation, various plant-based raw materials provide nutrients that are beneficial for sleep, such as GABA, an amino acid found in foods such as vegetables, fruits, and fermented products [68]. GABA can be derived from sprouted brown rice, wine fermentation, or from extracts of *Apocynum venetum* L. leaves. GABA plays a crucial role in the central nervous system, significantly shortening sleep latency while increasing NREM sleep duration. It is quickly absorbed, with blood levels peaking 30 min after oral administration before gradually decreasing. The effect of GABA on sleep may be linked to its levels in the bloodstream [12].

Food supplements. Food supplements are concentrated sources of nutrients, such as vitamins and minerals, or other substances that affect health. They are sold in the form of pills, tablets, capsules, or liquids with measured doses. These supplements may contain a variety of ingredients, including vitamins, minerals, amino acids, essential fatty acids, fiber, and plant or herbal extracts². Some food supplements are linked to improvements in sleep (Table 1). For example, essential amino acids can improve sleep by helping to produce certain neurotransmitters. Tryptophan, a dietary protein, may assist in sleep recovery after re-feeding following a period of calorie restriction. Since tryptophan competes to cross the blood-brain barrier, increasing its levels may help improve sleep efficiency. Milk proteins, plant proteins, or alpha-lactalbumin can also help improve sleep in adults with sleep disturbances caused by nutritional problems, shift work, or fasting during Ramadan [69].

Dietary supplements containing L-theanine (655 mg) and 5'-adenylic acid (53 mcg) have been shown to significantly reduce sleep onset time and could be used to promote natural sleep [70]. A combination of alpha-s1-casein tryptic hydrolysate and L-theanine in working adults with poor sleep quality improved their sleep onset time, sleep duration (by 45 min), sleep efficiency, and daytime functioning, as well as increased their alpha brain waves [71].

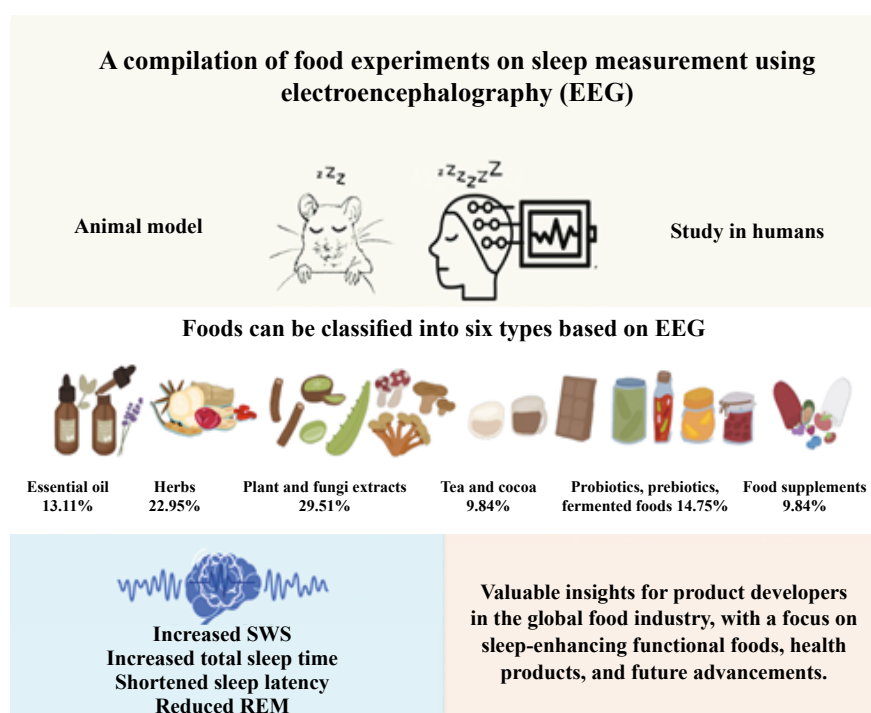
Zinc-containing yeast extract (40 and 80 mg/kg) increased the total amount of NREM sleep and reduced locomotor activity in a dose-dependent manner. Zinc, as an essential trace element, has the potential to interact with various synaptic targets, including glutamate and GABA receptors, and modulate their activity [72]. Glycine is a functional food that provides many beneficial phytochemicals. Administration of glycine extract (30 mg/kg) decreased wake time and increased both REM and NREM sleep in environmental prenatal stress-stressed rats [73]. Furthermore, blue mussel (*Mytilus edulis* L.) water extracts produced a dose-dependent reduction in sleep latency and an increase in sleep duration in pentobarbital-treated mice. It decreased sleep latency and induced NREM sleep while maintaining REM sleep [74].

Future prospects of sleep product development.

The development of sleep-related food products offers consumers an alternative approach to health care. By utilizing raw materials or food types supported by sleep-related data obtained through EEG, product developers can strategically select ingredients for prototype development. Sleep-inducing products provide individuals seeking improved sleep with a food-based alternative to pharmaceutical medications. The integration of EEG brainwave measurements with raw materials or food types enables the creation of functional foods. While certain foods may offer desirable taste and aroma, they may not necessarily enhance sleep functions. The combination of sensory evaluation with EEG data provides developers with the opportunity to create foods that are not only palatable but also contribute to improved sleep, thereby offering greater benefits to consumers (Fig. 2).

The use of EEG in analyzing raw materials or product types for sleep-inducing foods presents significant potential for real-world product development. EEG facilitates the analysis of brain waves and provides valuable insights into how these products may influence sleep following consumption. Based on available data, raw materials from six distinct food categories, when used within appropriate dose ranges, hold potential for developing sleep-promoting food products. The data suggests that food consumption can influence sleep, with a particular emphasis on SWS and NREM sleep over REM sleep. Several food products, including probiotics, fermented foods, tea, and cocoa, are already available and easily consumable, offering a wide range of options for consumers. In addition, raw materials that contribute to flavor, such as essential oils, can be incorporated into a variety of food products, particularly in Asian cuisines, where foods containing essential oils are commonly consumed.

² Food supplements. European Food Safety Authority. 2024 [cited 2024 Dec 5]. Available from: <https://www.efsa.europa.eu/en/safe2eat/food-supplements>



SWS – slow-wave sleep; REM – rapid eye movement

Figure 2 The role of electroencephalography in the development of sleep-related food products

According to Table 2, many foods and supplements exert a more pronounced effect on SWS than on REM sleep. The development of products that are easy to consume before bedtime, such as beverages or tablets, may help reduce beta waves and increase theta and delta waves, thus facilitating a quicker onset of sleep. While foods affecting REM sleep are less common, certain foods containing Chinese herbal medicines have demonstrated potential effects on sleep. They include *Aloe vera* aqueous extract, stilbene glucoside (*P. multiflorum*), *Pinellia rhizoma*, aluminum extract, lotus extract, *Lonicera japonica* Thunb. extract, and *E. longifolia* extract. These ingredients produce direct therapeutic effects on sleep-related conditions. Notably, these botanical ingredients contain bioactive compounds known to modulate sleep patterns through their sedative, anxiolytic, and anti-inflammatory properties, which may be particularly beneficial for individuals with insomnia or disrupted sleep.

For individuals accustomed to consuming caffeinated beverages, EEG data suggest that tea and cocoa may improve sleep quality. These foods may mitigate the stimulating effects of caffeine when consumed in controlled amounts, particularly in the evening. Therefore, the development of products in this category should focus on optimal dosages to shorten the NREM period and improve overall sleep quality. Incorporating ingredients such as theobromine from cocoa or L-theanine from tea may further enhance sleep-promoting effects by promoting relaxation and reducing sleep onset latency.

The design of sleep-related products must adhere to both international and national regulations regarding the permissible inclusion of sleep-inducing ingredients. It is essential to evaluate the safety and efficacy of these ingredients at specific dosages to ensure their suitability for marketing as food-based sleep aids. These products are a natural and accessible alternative to pharmaceutical sleep medications. This review can provide product developers with valuable insights into the potential of various ingredients tested through EEG analysis, as well as inform the development of novel sleep-related products. Future research should further explore the synergistic effects of different food components on sleep regulation, optimizing formulations that target specific sleep disorders while ensuring both safety and consumer acceptance.

CONCLUSION

The use of electroencephalography can serve as a valuable guideline in the development of sleep-related food products. Electroencephalography can measure the effects of food consumption on sleep, specifically during the slow-wave sleep stages. However, our data suggests that common foods tend to have a stronger impact on enhancing non-rapid eye movement sleep rather than rapid eye movement sleep. The observed changes in brain waves, including reductions in alpha and beta waves and increases in theta and delta waves, provide key insights into the effects of food consumption on sleep. Foods that extend the rapid eye movement stage are primarily Chinese herbal medicines, which are often more therapeutic than conventional food products. Six

sleep-related food categories identified through electroencephalography include essential oils, Chinese herbal medicines, plant and fungi extracts, tea and cocoa, probiotics and prebiotic-fermented foods, and food supplements. These products are available both as main dishes and supplements. By leveraging these insights to further develop these products, it is possible to create foods that not only taste appealing but also promote sleep-enhancing functions. This review provides valuable information for product developers in the global food industry, particularly in the functional food and health product markets, with a focus on future advancements.

CONTRIBUTION

A. Sattayakhom: conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing – original draft, review and editing; P. Koomhin: conceptualization, data curation, formal analysis, investigation, funding acquisition, methodology, project administration, resources, supervision, software, validation, visualization, writing –

original draft, review and editing; N. Matan: conceptualization, data curation, formal analysis, investigation, funding acquisition, methodology, project administration, resources, supervision, software, validation, visualization, writing – original draft, review and editing.

CONFLICT OF INTEREST

The authors have no conflict of interest regarding this publication.

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AI DECLARATION

During the preparation of our manuscript, the author(s) used ChatGPT and Gemini to check and polish the language and grammar. After using these tools/services, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the publication.

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