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EFFECT OF CIRCADIAN RHYTHM DISRUPTION ON FATIGUE AMONG PILOTS: NARRATIVE REVIEW

Dr. Sura Ashour Ibrahim*[1], Dr. Ibraheem Mohammed Al-Obaidi[2], Dr. Oday Taher Mohammed Al-Hashimi[3]

[1]Resident in Followship in Aviation Medicine, Joint Program of the Arab Board in Aviation Medicine.
[2]B. General, Flight Surgeon., Iraqi Aeromedical Center Commander. Neurosurgeon, Arab Board of Health, Specialization, (ABHS)_Neuro.
[3]Department of Medicine, College of Medicine, University of Baghdad, Baghdad, Iraq. PHD Arab Board Physician Medicine.

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***Corresponding Author: Dr. Sura Ashour Ibrahim**

Resident in Followship in Aviation Medicine, Joint Program of the Arab Board in Aviation Medicine.

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ABSTRACT

Background: The aviation environment exposes pilots to multiple circadian challenges including night operations, trans meridian travel, irregular scheduling, and fluctuating workload intensity. These factors contribute to acute and chronic fatigue, a recognized threat to operational safety and pilot health. **Objective:** This review synthesizes current scientific evidence on circadian rhythm biology, fatigue pathophysiology, demographic and operational risk determinants, and fatigue assessment tools, with a focus on applications to global aviation and emerging sectors such as Iraq. **Methods:** A narrative review approach was used to examine peer-reviewed studies published in aviation medicine, chronobiology, sleep research, and human factors. Databases searched included PubMed, Academic.edu, Aviat Space Environ Med, J Occup. Environ Med, SKY brary Aviation Safety, Elsevier Scopus, Web of Science, Web MD and Google Scholar. Study design included cross-sectional, cohort, review articles, thesis, survey, educational\ operational guidance, mixed method analysis and theoretical review in the last 20 years. **Key finding:** Findings demonstrate that circadian misalignment significantly impairs alertness, psychomotor function, decision-making, and sleep quality. Risk factors include age, chronotype, BMI, underlying medical conditions, night duties, long-haul operations, and environmental stressors. Validated tools such as the Epworth Sleepiness Scale (ESS) and Fatigue Severity Scale (FSS) remain central to fatigue evaluation. **Conclusion:** For rapidly developing aviation sectors, including Iraq, implementing a layered, evidence-based fatigue management strategy is essential to improve safety, enhance pilot performance, and protect long-term pilot health, as fatigue is a hazard that can be anticipated, prevented, and managed.

KEYWORDS: Such as circadian rhythm, pilot fatigue, aviation safety, chronotype, flight duty time, and fatigue risk management systems (FRMS).

1. INTRODUCTION

Fatigue is a major operational concern in aviation and is strongly influenced by circadian rhythm regulation. Circadian rhythms are natural, internal processes that follow 24-hour cycle and help regulate various biological functions. The term circadian comes from the Latin words circa diem, meaning (about a day).[1] The circadian system regulates sleep-wake patterns, hormone secretion, alertness, and cognitive performance, making its alignment essential for safe flight operations.[1,2] Pilots often experience circadian disruption due to night flights, early morning departures, long duty hours, and trans meridian travel, all of which impair neurobehavioral performance and increase the risk of operational errors.[3,4,5] The world is divided into 24 time zones, each approximately 15 degrees of longitude apart, but there are actually over 38 unique time zones in use today, including half-hour and quarter-hour offsets. Coordinated Universal Time (UTC) is the primary time standard by which the world regulates clocks and time.

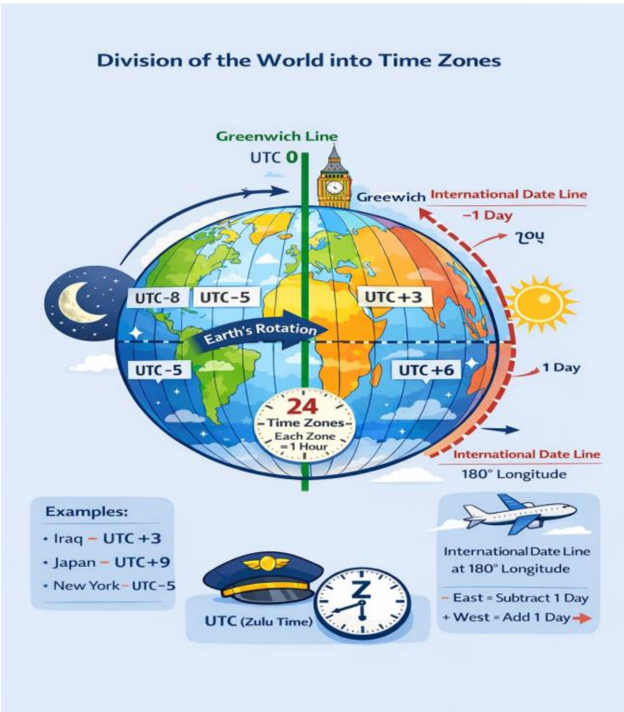
All time zones are expressed as positive or negative offsets from UTC.

Coordinated Universal Time (UTC), aligned with 0° longitude, serves as the baseline for all time zone calculations.[6]

Fatigue is a physiological state of reduced mental or physical performance capability resulting from sleep loss, extended wakefulness, circadian phase, and/or workload (mental and/or physical activity), that can impair a crew member's alertness and ability to safely operate an aircraft or perform safety-related duties. Fatigue physical signs include constant tiredness or lack of energy, heavy eyelids, yawing, headaches, micro-sleeps and reduced coordination. Fatigue cognitive signs like difficulty concentrating, memory lapses, slower thinking or reaction time, confusion and reduced problem-solving ability. Behavioral signs include fixation on one task, missed radio calls, reduced motivation, reduced communication and irritability. Fatigue may be acute, chronic or burnout. Studies show that fatigue-related impairment can mirror the cognitive deficits associated with alcohol intoxication, underestimating fatigue significance as a threat to aviation safety because fatigue is often greater operational danger, more common and harder to detect. Alcohol produces strong, dose dependent impairment while fatigue cause progressive and insidious impairment. Fatigued pilots often believe they are functioning adequately. Although the aviation workforce remains predominantly male, recent studies incorporating female pilots have begun to examine gender related differences in sleep behavior and fatigue vulnerability. Women generally report higher levels of subjective fatigue but tend to maintain more consistent sleep hygiene practices compared to their male counterparts. Hormonal fluctuations may also influence circadian rhythm stability and sleep architecture. However, due to the limited representation of women in aviation studies, the role of gender remains insufficiently characterized.[7,8]

Multiple factors contribute to heightened fatigue risk in pilots, including chronotype, age, sleep quality, workload, duty schedules, and environmental disruption during layovers. Eastward flights, in particular, produce greater circadian misalignment due to the difficulty of advancing the biological clock.[9,10,11,12] Regional and environmental conditions, such as extreme temperature, security-related disruptions, or infrastructural constraints as observed in some Middle Eastern aviation sectors may further exacerbate circadian strain, reduce sleep opportunities and their effect on regulation of clocks and time.[11] Helicopter pilots accumulate fatigue rapidly due to frequent early starts, calls, and fragmented sleep, whereas fixed-wing pilots typically experience fatigue during prolonged duty periods or trans meridian travel. Helicopter pilots suffer from unpredictable sleep due to irregular roster which disrupt sleep-wake patterns and reducing sleep predictability and short-duration sleep, while fixed-wing pilots face scheduled but phase-shifted sleep loss due to jet lag.[3,9,13]

For circadian influences on pilots fatigue, comprehensive evaluation strategies including biomathematical models, subjective scales, and fatigue risk management systems (FRMS) have been recommended. This review synthesizes current evidence on how circadian rhythm disruption affects pilot fatigue and examines operational, physiological, and environmental factors that modify fatigue risk.[14,15]



2. METHODS

A narrative review methodology was used to examine the relationship between circadian rhythm disruption and fatigue among pilots. Relevant studies were identified through searches of PubMed, Academic.edu, Aviat Space Environ Med, J Occup. Environ Med, SKY brary Aviation Safety, Elsevier Scopus, Web of Science, Web MD and Google Scholar using keywords such as circadian rhythm, pilot fatigue, aviation safety, chronotype, flight duty time, and fatigue risk management systems (FRMS).

Articles published in English language between 2005 and 2025 were included. Study design included cross-sectional, cohort, review articles, thesis, survey, educational\ operational guidance, mixed method analysis and theoretical review. Search through 107 research and review about circadian rhythm disruption and fatigue in general, 84 of them screened, 56 were eligible and 36 were included.

Additional inclusion criteria consisted of studies assessing fatigue in pilots, research examining circadian biology or sleep regulation relevant to aviation, and investigations exploring operational or environmental contributors to fatigue.[12,14,15] Exclusion criteria included studies unrelated to aviation, those lacking circadian relevance, or papers with insufficient methodological quality.

Data were extracted on circadian mechanisms, fatigue assessment tools, risk factors, operational variables, and mitigation strategies. The findings were synthesized qualitatively due to variability in study designs and measurement methods according to matching to research questions or keywords, author and publication sources, objectivity, data publication and study design, using valid tools like ESS.[3,8,15]

2.1. Strengths and Limitations

Strengths

Comprehensive synthesis across multiple disciplines
Relevance to both global and regional aviation contexts
Structured identification of risk domains

Limitations

Narrative rather than systematic design
Limited region-specific data for the Middle East and Iraq
Heterogeneity in study designs across the literature

2.2. Gaps and Controversies

Despite extensive research on fatigue and circadian misalignment in aviation, several knowledge gaps and controversies remain, limiting the ability to fully implement evidence-based interventions:

➢ **Limited Region-Specific Research**

Most fatigue studies have been conducted in Western populations, particularly in Europe, North America, and Australia. There is a paucity of data from the Middle East, including Iraq, where pilots may face unique operational challenges such as extreme heat, infrastructure limitations, and civil-military flying duties sharing the same airspace. This limits the generalizability of existing findings and calls for region-specific studies to inform tailored fatigue risk management systems (FRMS).

➢ **Heterogeneity in Study Designs and Measurements**

Studies on pilots fatigue vary widely in methodology, including differences in sample size, duty patterns, flight types (short-haul vs long-haul), and assessment tools (subjective scales vs objective biomathematical models).[2,23] This heterogeneity complicates comparisons across studies and reduces confidence in pooled conclusions. Standardized methodologies are still lacking.

➢ **Chronotype and Individual Variability**

The interaction between chronotype (morning/ evening) and duty schedules is recognized as a key determinant of fatigue, yet most research treats pilots as a homogeneous group.[17,21] The effectiveness of chronotype-based rostering remains controversial, and the distribution of chronotypes in regional pilots populations is largely unknown.

➢ **Objective vs. subjective measures of fatigue**

While subjective tools like the Epworth Sleepiness Scale (ESS) and Fatigue Severity Scale (FSS) are widely used, their correlation with actual operational performance is inconsistent.[3,24] Some pilots may underreport fatigue due to cultural or professional pressures, while others overreport due to heightened awareness. The lack of universally accepted objective biomarkers for fatigue remains a challenge.

➢ **Long-Term Health Consequences**

Although circadian disruption has been linked to cardiovascular, metabolic, and mental health disorders, longitudinal studies tracking these outcomes in pilots are limited.[19,20] Most research focuses on acute operational impairment, leaving the chronic health effects of repeated circadian misalignment underexplored.

➢ **Effectiveness of Fatigue Mitigation Strategies**

Fatigue Risk Management Systems (FRMS), napping strategies, and pharmacological interventions (e.g., caffeine or melatonin) have shown promise, but their efficacy in diverse operational contexts is debated.[4,9] There is limited evidence on long term compliance and real world effectiveness, particularly in high stress or resource constrained environments.

➢ **Environmental and Contextual Factors**

Layover conditions, local time-zone differences, hotel quality, climate, and security concerns can all influence sleep quality and circadian adaptation, but these factors are often underrepresented in studies.[10] The relative contribution of environmental versus operational determinants of fatigue is still unclear.

➢ **Controversy over Duty-Time Regulations**

Current prescriptive flight-time limitations are criticized for not accounting for individual differences in circadian vulnerability or cumulative fatigue.[27] Some researchers argue for biomathematical, predictive approaches, but implementation faces logistical, regulatory, and ethical challenges.

3. DISCUSSION

This review highlights the substantial influence of circadian rhythm disruption on pilots fatigue and its critical implications for aviation safety. Circadian rhythm disruption emerged as a primary cause of fatigue in pilots. Fatigue is highly prevalent in both commercial and military pilots due to long duty hours, irregular schedules, and time zone crossing. Short-haul pilots: 30–50% report significant fatigue during duty periods. Long-haul pilots: up to 70% experience fatigue due to circadian misalignment and extended duty periods military helicopter pilots: social jet lag correlated with higher subjective sleepiness scores. Commercial airline pilots: 41–67% show irregular sleep patterns; 29–33% report fatigue symptoms.[10,13] Multiple studies highlighted significant declines in alertness, reaction time, and decision-making during the window of circadian low between 02:00 and 06:00.[1,7] Night flights, early-morning departures, and eastward trans meridian travel were consistently associated with greater circadian misalignment and fatigue severity.[2,3] Individual factors such as chronotype, age, and health status influenced fatigue susceptibility. Evening-type pilots experienced more pronounced impairment during early-morning duties, whereas morning types struggled with night operations.[9,23] Age related reductions in circadian plasticity led to slower adaptation to time-zone shifts in older pilots.[1,23] Elevated BMI, sleep disorders were also found to worsen sleep quality and daytime alertness[25,26], the type of aircraft operated is closely linked to route length and mission profile, both of which significantly influence circadian rhythm stability and fatigue levels among pilots. Long-haul pilots typically flying wide-body aircraft such as the Boeing 777 or Airbus A350 are exposed to extended duty periods, frequent trans meridian travel, and overnight operations. These factors contribute to substantial circadian misalignment and increased vulnerability to jet lag.[17,24,25] Circadian rhythm disruption due to operational workload including long duty periods, multiple flight legs, and irregular rostering was strongly linked to cumulative fatigue.[8,11,14] Challenges noted in certain regional aviation environments, including heat exposure and inconsistent accommodations, contributed to reduced sleep opportunities and higher fatigue levels.[13,26]

Assessment tools such as the Epworth Sleepiness Scale, Fatigue Severity Scale, and biomathematical fatigue models were commonly used and demonstrated reliability in measuring fatigue risk.[14,27] Studies evaluating fatigue mitigation strategies consistently reported that FRMS implementation improved pilot alertness and operational safety compared to traditional prescriptive duty regulations.[9,12,15] Extensive evidence demonstrates that misalignment between the endogenous circadian system and operational demands leads to reductions in alertness, cognitive performance, and psychomotor speed, with impairments comparable to low-dose alcohol intoxication.[5,7,8] These deficits directly increase the likelihood of operational errors, incidents, and accidents in aviation environments.[4,5,20]

Circadian misalignment is most pronounced during night operations, early-morning departures, and trans meridian flights particularly eastward travel, which requires more difficult phase advancement of the biological clock.[1,2,3] The window of circadian low occurring between 02:00 and 06:00 represents a period of heightened vulnerability in which sleep pressure peaks and neurobehavioral performance declines significantly.[1,7] Even well-rested pilots experience substantial reductions in reaction time and decision-making accuracy during these hours.

The cumulative interaction between circadian misalignment and sleep restriction directly impairs a range of cognitive and operational functions essential for flight safety. Fatigue has been shown to degrade situational awareness, reaction time, risk assessment, communication effectiveness, and crew resource management behaviors.[7,8,28] This impairment can occur even when pilots underestimate their level of sleepiness, indicating a dangerous gap between subjective perception and objective fatigue levels.[14,16]

Individual physiological and demographic factors also contribute to variability in fatigue susceptibility. Chronotype plays a key role; evening type individuals experience pronounced difficulty with early-morning duties, while morning types struggle with extended night operations.[10,29] Age-related reductions in circadian adaptability further impair recovery from jet lag among older pilots.[1,16] Additional factors such as sleep disorders, thyroid dysfunction, obesity can significantly disrupt sleep architecture, impair physiological recovery, and exacerbate fatigue symptoms, smoking; nicotine and other constituents in tobacco influence circadian physiology via clock gene modulation, neurotransmitter and hormone alterations, sleep architecture disruption and sympathetic overactivation., and strict limits on alcohol use typically prohibiting consumption within 8–12 hours of duty and requiring a blood alcohol concentration below 0.02% habitual drinking patterns outside duty hours may still compromise sleep and circadian alignment.[19,20,30,31,32]

Operational and environmental conditions further compound fatigue. Extended duty periods, multiple flight legs, high workload intensity, and irregular roster patterns are consistently associated with increased fatigue among pilots.[33,34] Sleep during layovers is frequently non restorative due to noise, temperature fluctuations, light exposure, and unfamiliar environments.[12,26] These challenges are magnified in regions with harsh climates or varied infrastructure. Pilots operating in Iraq, for example, face extreme heat and security-related sleep disturbances, which exacerbate circadian strain.[12,27,28]

Validated tools such as the Epworth Sleepiness Scale, Fatigue Severity Scale, Karolinska Sleepiness Scale, and biomathematical models provide objective means of assessing fatigue risk.[7,21,22,35] However, reliance solely on prescriptive duty-time regulations remains insufficient, as these limits do not capture individual physiological variability or circadian factors.[12,22] Evidence strongly supports the adoption of Fatigue Risk Management Systems (FRMS), which offer a proactive, data-driven framework for mitigating fatigue and improving operational safety.[12,22,26,35]

Another recurring theme across the literature is the need for improved education on circadian science and fatigue management among pilots and schedulers. Training on topics such as sleep hygiene, strategic use of light exposure, caffeine timing, and jet lag countermeasures enhances self- management and operational resilience.[13,36] Furthermore, optimizing roster design, minimizing circadian disruption, and ensuring adequate recovery periods after long-haul or night operations are essential for reducing cumulative fatigue.[23,26]

Despite the substantial body of international research on aviation fatigue, region specific data particularly from Middle Eastern and developing aviation sectors remain limited. Additional studies are needed to explore how environmental, cultural, and operational factors specific to Iraq and similar regions influence fatigue patterns among pilots. Further research on chronotype based scheduling, long term health effects of chronic circadian disruption, and the relationship between metabolic health and fatigue resilience would also strengthen future FRMS policy development.

Overall, the evidence consistently demonstrates that circadian rhythm disruption is a major driver of fatigue among pilots, interacting with biological, operational, and environmental determinants. Mitigation requires a multilayered strategy that integrates circadian science, evidence-based scheduling, robust FRMS frameworks, and context specific policies tailored to regional aviation realities.

The findings of this review hold particular relevance for emerging aviation sectors such as Iraq, where pilots face distinctive operational stressors. Extreme heat, shifting work schedules, infrastructure variability, civil and military sharing the same aviation environments, may amplify fatigue risk and interfere with stable circadian entrainment.[26,27,28] These region specific conditions can limit sleep quality during layovers and exacerbate cumulative fatigue, particularly for long-haul and night-flying pilots.[7,18,29]

Additionally, evolving regulatory frameworks in emerging markets may not yet fully align with ICAO's Fatigue Risk Management System recommendations. Tailoring to Fatigue Risk Management System address region specific climate, cultural, and operational realities is essential to improving pilot safety and sustaining aviation growth in the region.[37]

3.1. Limitations and Future Research

This review is limited by its narrative design and by heterogeneity among included studies. Additionally, a lack of region-specific research from the Middle East, particularly Iraq, constrains the ability to draw detailed contextual conclusions.[40] Future research should prioritize:

- Field studies measuring real-time fatigue among regional pilots
- Validation of biomathematical models in hot-climate
- Chronotype profiling of local pilot populations
- Culturally adapted fatigue-reporting systems

Such efforts would support evidence-based FRMS development across diverse operational environments.

Table 1: Summary of operational factors influencing fatigue in aviation.

Operational Factor	Mechanism of Fatigue	Impact on Pilot Performance	Examples
Night flights / red-eye operations	Circadian disruption	Reduced vigilance, slower reaction time and decision making	02:00-06:00 a.m.
Early morning departures	Sleep restriction, misalignment	Impaired decision-making	04:00–06:00 takeoffs
Ultra-long haul flights	Extended wakefulness	Cumulative fatigue	>14-hour flights
Multi-sector regional flights	Frequent takeoffs/landings	Mental overload	4–6 short-haul legs
Rapid time zone transitions	Phase-shift misalignment	Jet lag, cognitive slowing	Transcontinental flights
Irregular rosters	Unpredictable sleep	Higher fatigue variability	Non-structured schedules

Table 2: Summary of environmental factors during layovers and their effects in aviation.

Environmental Factor	Effect on Sleep	Consequences for Fatigue	Most Affected Regions
Hotel noise	Fragmented sleep	Increased daytime sleepiness	Urban Asia, Gulf cities
Extreme heat	Reduced sleep efficiency	Chronic fatigue accumulation	Middle East, Africa
Poor accommodation quality	Lower comfort, insufficient recovery time	Reduced sleep duration	Developing countries
Irregular meal timing	Delayed circadian cues	Slower adaptation to time zone	Long-haul layovers
Security concerns	Hypervigilance	Inability to enter deep sleep	Conflict affected regions

Table 3: Comparison of common fatigue measurement tools.

Tool	Type	Measures	Strengths	Limitations
ESS (Epworth Sleepiness Scale)	Subjective	Daytime sleepiness	Simple, widely used	Underreporting possible
KSS (Karolinska Sleepiness Scale)	Subjective	Real-time alertness	Useful during operations	Moment-only measurement
FSS (Fatigue Severity Scale)	Subjective	Chronic fatigue	Good for long-term	Lack of operational specificity
Actigraphy	Objective	Sleep duration & efficiency	Real-world data	Expensive, requires compliance
PVT (Psychomotor Vigilance Test)	Objective	Reaction time	Strong predictor of errors	Requires equipment
SAFTE / FAID biomathematical models	Predictive	Fatigue risk scoring	Useful for scheduling	Based on assumptions

Table 4: Comparison between Middle Eastern / Iraqi and Western Aviation Fatigue Research.

Domain	Western Findings	Middle Eastern / Iraqi Findings
Sleep duration	Well documented across airlines	Understudied, reports show shorter layover sleep
Environmental stressors	Typically good quality hotels	Issues: heat, noise, safety concerns
Schedule regularity	More regulated rosters	More variability in rosters
Cargo operations	High fatigue, night operations	Similar but with additional thermal stress
FRMS implementation	Advanced, data driven	Developing, variable across operators
Pilot reporting culture	Structured, non punitive	Underreporting due to cultural/organizational factors

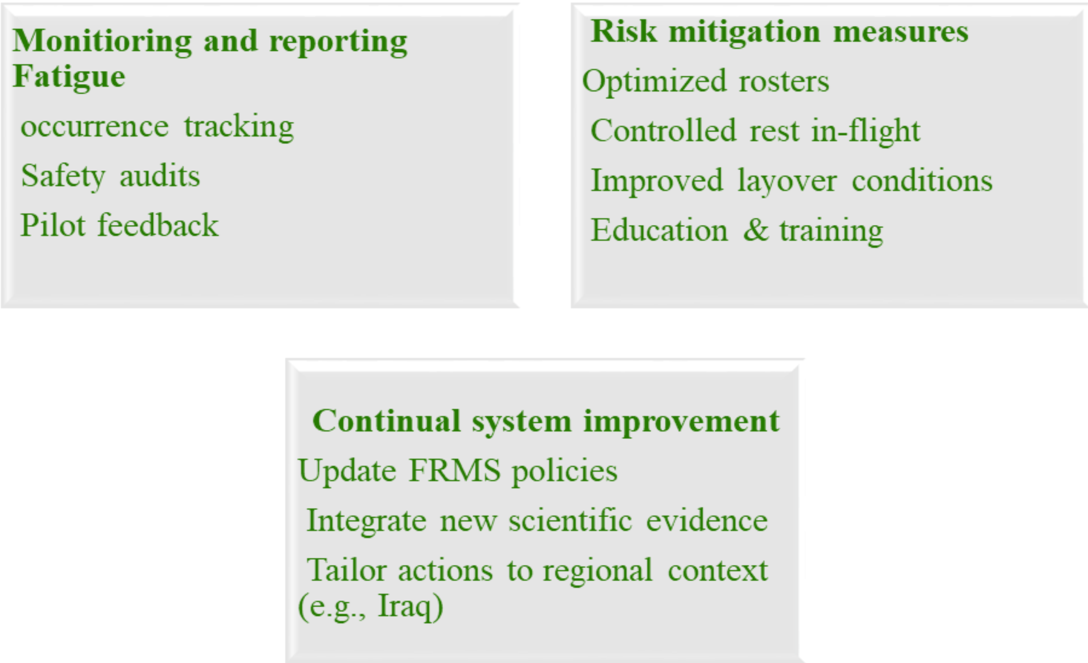


Figure 1: Flowchart of FRMS (Fatigue Risk Management System).

4. Recommendations

Based on the findings of this review, the following recommendations are proposed to enhance pilots safety and mitigate fatigue related risks:

- **Implement comprehensive fatigue risk management systems (FRMS)**

Airlines and regulatory authorities should adopt FRMS aligned with ICAO guidelines to systematically identify, monitor, and mitigate fatigue. These systems should integrate circadian science, operational realities, and individual differences.[40]

- **Use biomathematical fatigue prediction models**

Scheduling departments should incorporate validated tools such as SAFTE or FAID to identify high-risk duty patterns, particularly during night operations, extended duty periods, and eastward time-zone transitions.

- **Integrate chronotype assessments in roster planning**

Routine evaluation of pilot chronotype may allow more individualized scheduling, reducing circadian strain and improving sleep outcomes.[38,39]

- **Enhance training in sleep science and fatigue management**

Pilots training programs should include evidence-based modules on circadian rhythms, sleep hygiene, fatigue countermeasures, and controlled napping strategies.

- **Standardize rest and layover environments**

Operators should ensure that pilots rest facilities and layover accommodations provide noise control, adequate temperature regulation, blackout capabilities, and security particularly in regions with extreme climates or infrastructure limitations.

- **Strengthen medical screening for sleep disorders**

Routine screening for conditions such as obstructive sleep apnea, insomnia, and circadian rhythm disorders should be integrated into aviation medical assessments, with accessible pathways for diagnosis and treatment, ESS can be used as screening tool.

- **Promote healthy lifestyle practices**

Airlines should support programs that encourage physical activity, balanced nutrition, tobacco cessation, and moderated alcohol use, all of which influence sleep quality and fatigue vulnerability.

- **Develop region-specific policies for emerging aviation markets**

In contexts such as Iraq, regulatory authorities should consider environmental and operational factors extreme heat, civil and military flying duties because in some regiones sharing the same airspace, and variable infrastructure when designing fatigue management policies.

- **Encourage non-punitive fatigue reporting**

A safety culture that supports open communication and non-punitive reporting of fatigue will improve data collection and facilitate early intervention.

- **Conduct operational research in understudied regions**

Future studies should focus on field measurements of fatigue among pilots in the Middle East and similar environments to inform localized, evidence-based countermeasures.

5. CONCLUSION

For rapidly developing aviation sectors, including Iraq, implementing a layered, evidence-based fatigue management strategy is essential to improve safety, enhance pilot performance, and protect long-term pilot health, as fatigue is a hazard that can be anticipated, prevented, and managed.

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