IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 3, July 2026
Impact Factor: 8.2

Artificial Intelligence for Sleep Analysis Using EEG Data: A Comprehensive Review

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Abstract: *Sleep is a complex mixture involving both the brain and the body. When the sleep routine is disturbed, it negatively affects our health and the efficiency of the brain. Traditional methods used to study sleep is expensive, time-consuming and require experts to analyse the results. Therefore, we use AI to make these tests easily accessible. The integration of Machine Learning and Deep Learning has opened new possibilities to improve the study of sleep. It could lead us to detect problems and monitor sleep over time without needing experts.*

The study focuses on extracting meaningful features from recorded sleep data and classifying them into their stages. It examines sleep-related disorders, sleep patterns, and brain health. Additionally, the role of wearable technology in continuous sleep monitoring is discussed. Importantly noted that algorithmic fairness, data privacy and adaptive and explainable systems are taken into consideration. This way, we can keep sleep and brain health under regular checkup.

Keywords: Sleep, Machine Learning, Deep Learning, Sleep, Electroencephalography (EEG), Sleep Staging, Polysomnography, Sleep Disorders, PTSD, REM Sleep, Headsets, Convolutional Neural Networks, Explainable AI

I. INTRODUCTION

Sleep is essential for our bodies to work properly. During sleep, the body starts restorative processes which include fixing memories, keeping our hormones in balance and controlling our emotions. A large number of people suffer from sleep-related issues. The WHO says that a lot of people have insomnia, and many others have sleep Apnea affect millions of individuals worldwide. Diagnosing sleep patterns involves specialised tests conducted in a sleep lab, where doctors monitor brain activity and bodily functions throughout the night. This gives a large amount of imprecise data at an expensive cost and is even time-consuming. Here we bring in machine learning, offering a promising solution that understands the complex datasets of the human world. It detects irregularities and observes patterns with greater consistency. Deep learning is an element of machine learning that is effective in processing complicated data like sleep study data. The algorithm helps diagnose sleep disorders quickly and precisely. They can also help us monitor people's sleep over time, which aids in determining the right treatment. This paper discusses how machine learning and deep learning are used to analyse sleep data. We will cover how sleep works, how we can use computers to analyse sleep data, and how these technologies are applied in diagnosing sleep disorders. We will also address some challenges of using these programs in practice. The goal of this paper is to serve as a resource for researchers and doctors interested in using machine learning and deep learning to assist people with sleep disorders. Sleep and machine learning are two areas that can help us better understand sleep and its related disorders.[1] ,[4]

II. SLEEP ARCHITECTURE AND EEG CHARACTERISTICS

It is imperative to know what the electroencephalogram tells us about sleep before we proceed to discuss how AI uses EEG data Human sleep is not just one state. It consists of an organized sequence of distinct neurophysiological stages, each with its own electrographic pattern [6]. The challenge for any automated system is that these patterns overlap, change over time, and vary greatly between individuals.

2.1 Sleep Stages: Neurophysiological Foundations

There are two types of sleep, according to AASM classification: Non-Rapid Eye Movement and Rapid Eye Movement Non-Rapid Eye Movement sleep has stages, including N1, N2 and N3. Then there is Rapid Eye Movement sleep. This whole cycle takes 90 minutes and it repeats itself four to six times during the night. The early cycles are mostly made up of N3 slow-wave sleep. The later cycles have long and complex episodes of Rapid Eye Movement sleep. If this cycle is disrupted at any point it can have effects.

The first stage of Non-Rapid Eye Movement sleep is N1, which is also called sleep. This is when we start to fall. At this stage our brain is not very active. We have slow and rolling eye movements. The N1 stage does not last long it is only about 5-10% of our total sleep time.

The N2 stage is the part of our sleep cycle it is about 50% of our total sleep time. During this stage we have sleep spindles and K-complexes. Sleep spindles are like bursts of activity in our brain and K-complexes are big waves that help us stay asleep. These are very important for doctors to understand when they are trying to diagnose sleep problems.[10]

The N3 stage is the most refreshing part of our sleep. This is when our brain waves are very slow and we are still. This stage is very important for our body to recover from the day. For our immune system to get stronger. It is also when we store memories. This stage is affected a lot by aging and sleep disorders so it is very important to measure it. However, REM sleep differs greatly from NREM sleep. The brain is highly active while the body remains paralyzed. It is during this stage that dreaming occurs.[7]

2.2 EEG frequency bands and Sleep Staging

EEG signals show what is going on in the brain across frequency bands. There is delta, which ranges between 0.5 Hz and 4 Hz; theta, ranging from 4 to 8 Hz; alpha, ranging between 8 Hz and 13 Hz; sigma or spindle, ranging between 11 Hz and 16 Hz; and finally beta, which ranges between 13 to 30 Hz. These are the frequency bands that help determine the stage of sleep a patient is undergoing. There is also gamma activity, which is more than 30 Hz, and this is important for what happens in our brain when we are dreaming. Each of these frequency bands tells us something about what is going on in the brain. The way they change throughout the night is predictable.[8]

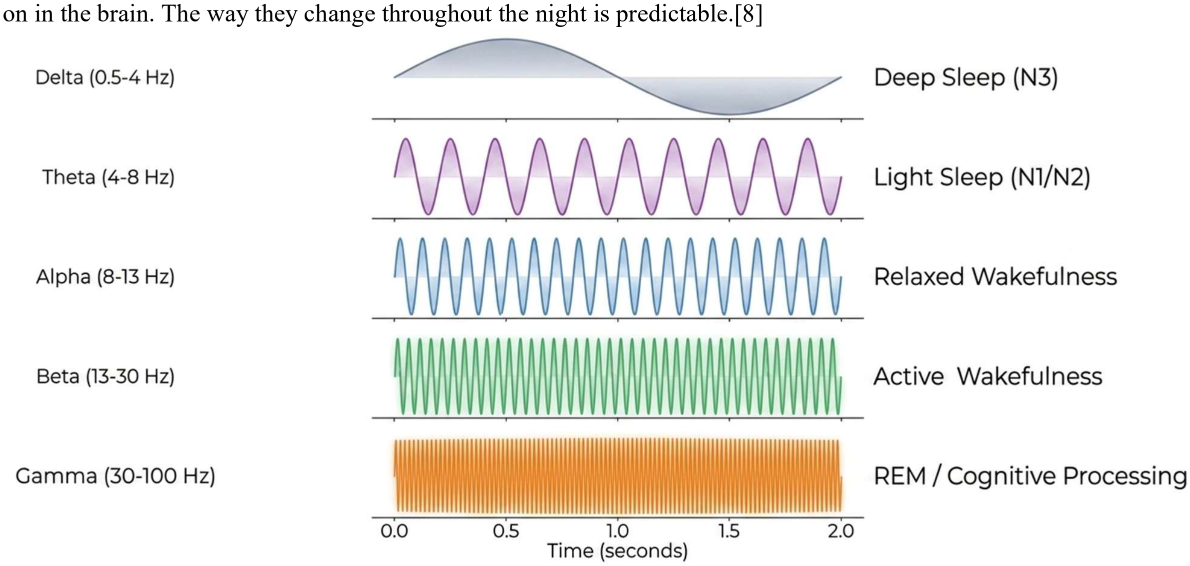

Figure 1: EEG frequency bands and their physiological associations across sleep stages [6]

The way EEG signals change throughout the night makes it possible for computers to figure out what stage of sleep a person is in. If we train computers on the frequency bands they can tell what stage of sleep a person is in almost as well as a human expert can. In some cases the computer is even better at it than a human.It is pretty surprising that computers can do this because people are all different and our brains do not all work the way. It just shows that computers can be really good, at understanding what is going on in our brains when we are sleeping. EEG signals and computers can work well together to help us understand sleep.

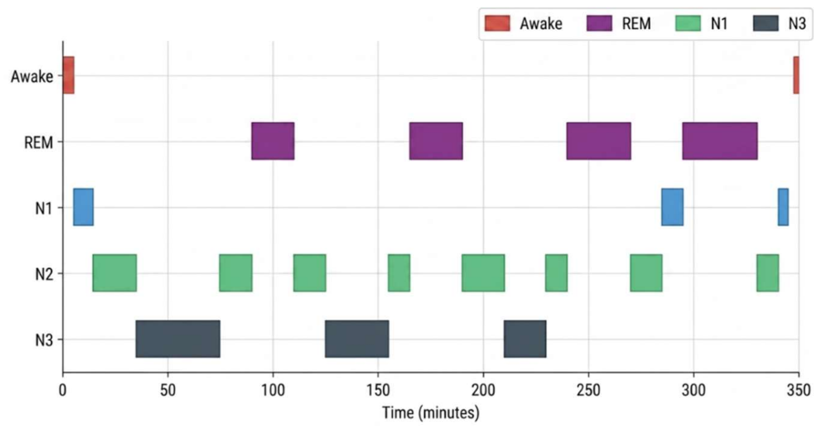

Figure 2: Representative sleep hypnogram illustrating the cyclic progression of sleep stages across a 7-hour night. REM periods lengthen progressively with each cycle while N3 predominates in early cycles.[5],[6]

III. THE IMPERATIVE FOR ARTIFICIAL INTELLIGENCE IN SLEEP RESEARCH

Manual sleep scoring is still considered the way to do it in clinics, but it has some big downsides. The problems are not small issues that we can fix quickly. The problems associated with collecting data are big. They limit the amount of data we can collect and how consistent the data is. [9]

3.1 Limitations of Conventional Sleep Analysis

Sleep plays an important role in overall health, and it occupies nearly one-third of human life. The number of experts is not enough, so a lot of people have to wait a long time and not everyone can get help easily. Different specialists may give different results, which may get confusing and make it hard to trust the data for treatment. The lab setting itself can also be a problem. Sleeping in a lab with wires attached can be uncomfortable. It is also hard to keep monitoring people for a long time, which is what many sleep disorders require.[12]

3.2 Advantages of AI-Driven Analysis

AI systems can help with these problems in ways:

- This includes changes that can predict sleep problems before they get serious.
- One of the things about AI is that it is consistent.

A trained AI model will look at every piece of data in the way without getting tired or making mistakes. It can also handle amounts of data without needing more staff, which is something that human experts cannot do. Another advantage of AI is that it can use different types of data at once. By looking at EEG data, AI can also use data from EOG, EMG and other physiological signals. This gives a complete picture of sleep patterns than any one type of data can. The result is not just as good as what a human expert can do, with all the data. It is actually better.[13]

DOI: 10.48175/IJARSCT-37855

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IV. AI TECHNIQUES FOR EEG-BASED SLEEP ANALYSIS

The process of using computers to analyse sleep, with EEG goes through steps. It starts with getting the signals and ends with giving doctors information they can use. Each step can do something and also has things that can go wrong. To really know how well the whole system works you have to look and understand how the EEG sleep analysis system.

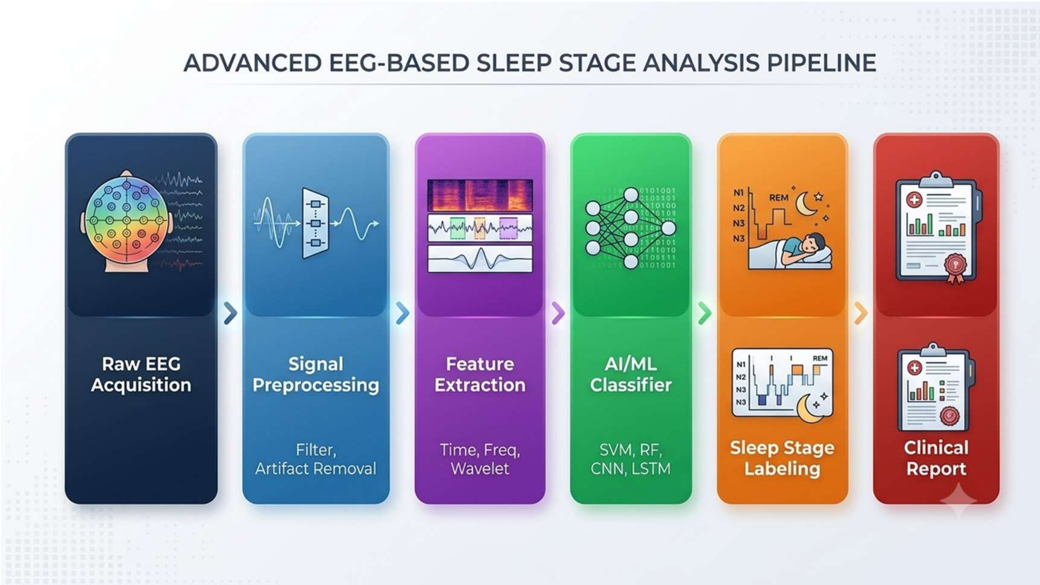

Figure 3: End-to-end AI flowchart for EEG-based sleep analysis, illustrating the sequence-wise transformation from raw bio signal acquisition to structured clinical reporting.[3]

4.1 Signal Pre-processing

When Raw EEG signals first come in they are not very clean. Moving our eyes around adds a lot of noise to the Raw EEG signals. This noise is really bad when we use Raw EEG to determine if we are in the N1 or REM stage of sleep. Our muscles also add a lot of high-frequency noise to the Raw EEG signals. Sometimes the electrodes do not work well, which can make the Raw EEG signals drift and look like they are doing something they are not doing. To fix these problems, we use some methods. We filter out the parts of the signal, like the low frequencies that come from our eyes moving and the high frequencies that come from the muscles. We also use tools to remove the noise from the signal. After that, we break the signal into parts that are 30 seconds long. This is what the American Academy of Sleep Medicine says we should do.[14]

4.2 Feature Extraction

Then we take these parts of the signal and turn them into something that the computer can understand. We use three ways to do this. The first way is to look at the signal and find things like the variance and other properties. This is fast and easy to do. It does not tell us much about what is going on in the signal. The second way is to look at the signal in the frequency domain. This means we look at the frequencies that are in the signal. We can use this to figure out what stage of sleep we are in. This is because the different stages of sleep have frequency patterns. The third way is to look at the signal in both the time and frequency domains at the same time. This is like taking a picture of the signal. It helps us see things that are happening at the same time. This is useful because the signal is always changing, and this method helps us see those changes. Lately, people have been using learning to look at the EEG signals. In this regard, the computer learns from the signals without having to teach it anything. The results have been very successful, although it is difficult to interpret the learning process of the computer. This is a challenge as understanding the processes is important since it will be applied to solve human problems. Time-domain features are things like the mean and variance of the signal [17]

- Frequency-domain features are things like the power in frequency bands [18]
- Time-frequency features are things like the Continuous Wavelet Transform and the Short-Time Fourier Transform

The EEG signal is used to figure out what stage of sleep we are in. The signal is broken into parts. Then we use these parts to train a computer to recognise the different stages of sleep. The computer can learn to recognise the stages of sleep by looking at the EEG signal. [19].

4.3 Machine Learning Classification Models

Sleep staging has been done with the help of Classical Machine Learning algorithms for a long time. These algorithms work with sets of features that people designed. They have been used since the 2000s. One of these algorithms is called Support Vector Machines. It is good at its job. Can accurately tell the stage of sleep about 78 to 82 per cent of the time. Another algorithm is called Random Forest. It is also very good and can accurately tell the stage of sleep about 80 to 83 per cent of the time. This is because it uses decision trees that work together. There are also algorithms like Linear Discriminant Analysis and k-Nearest Neighbour. [19]

4.4 Deep Learning Architectures

Deep learning has really changed how we do sleep staging. It helps us get accurate results. One type of learning is Convolutional Neural Networks. This looks at brain waves. It finds patterns that're hard for humans to see. For example, there is a kind of Convolutional Neural Network called Deep Sleep Net. It uses two parts to look at brain waves. One part looks closely at details. The other part looks at the picture. It can tell what stage of sleep someone is, in about 82 to 87 per cent of the time. Both methods make sleep staging more accurate. These technologies are helping us understand sleep better. Deep Sleep Net is one of the tools that is making this happen. There are also Recurrent Neural Networks and LSTM Networks. They look at the brain waves over time. Can see how they change. They are especially good at looking at the boundaries between stages of sleep. This is because they can look at what happened and what will happen after. Then there are Transformer-based Architectures. They are the most accurate ones. They can look at the brain waves over a period of time and find patterns that are not visible to the human eye. For example, there is a kind of Transformer-based Architecture called AttnSleep (deep learning architecture). It can accurately tell the stage of sleep 90 to 92 per cent of the time. Finally, there are Hybrid CNN-LSTM and Graph Neural Networks. They combine the strengths of algorithms to get even more accurate results. They look at the brain waves and the connections between parts of the brain. They can accurately tell the stage of sleep. Also find patterns that are not visible to the human eye.

These algorithms are good at their job. Can help us understand sleep better.

- They can look at the brain waves. Find patterns that are not visible to the human eye.
- They can accurately tell the stage of sleep.
- They can find patterns that are not visible to the human eye.

These are some of the ways that deep learning has changed the game for sleep staging. Sleep staging is done with the help of these algorithms. Sleep staging is an area of research. Sleep staging has applications [24].

4.5 Model Performance Comparison

Table 1: Comparative Performance of Representative AI Models for Five-Class EEG Sleep Staging

Model	Architecture	Accuracy (%)	F1-Score (%)	Kappa	Reference
SVM+Bandpower	Classical ML	78.4	76.2	0.72	Liang et al., 2012

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Model	Architecture	Accuracy (%)	F1-Score (%)	Kappa	Reference
Random Forest	Ensemble ML	82.1	80.3	0.76	Fraiwan et al., 2012
DeepSleepNet	CNN+BiLSTM	87.6	85.9	0.83	Supratak et al., 2017
SeqSleepNet	RNN+Attention	88.9	87.4	0.85	Phan et al., 2019
AttnSleep	Transformer	91.3	90.1	0.89	Eldele et al., 2021
Hybrid CNN-LSTM	CNN+LSTM	90.1	89.3	0.87	Phan et al., 2022

Table 1: Performance metrics on the Sleep-EDF benchmark dataset. Accuracy and F1-score are macro-averaged across five AASM sleep stages.[39]

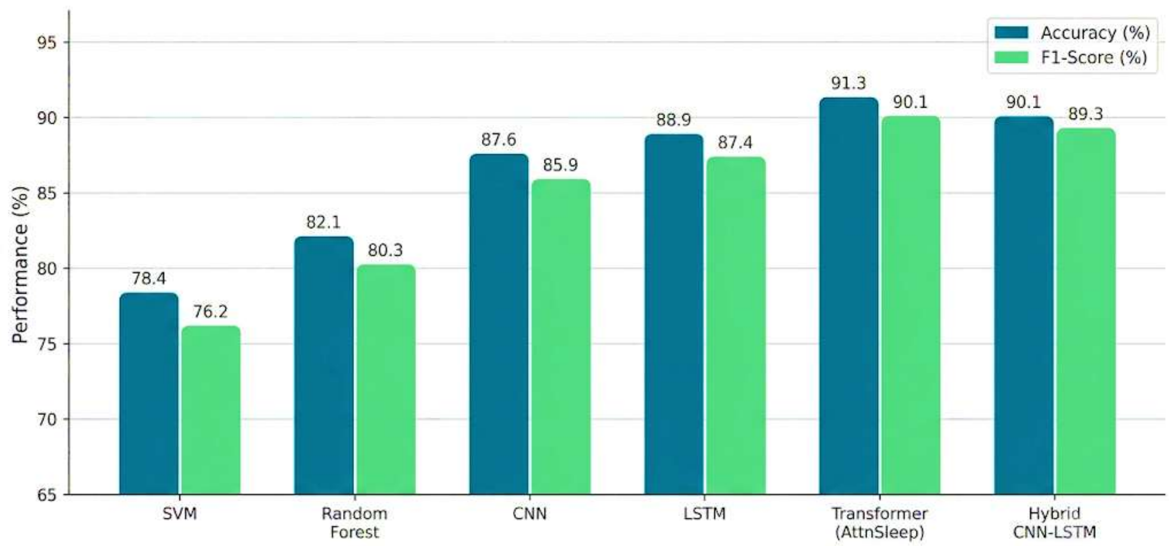

Figure 4: Visual comparison of accuracy and macro-averaged F1-score for representative AI models evaluated on standardized EEG sleep staging benchmarks.[26]

V. CLINICAL APPLICATIONS IN SLEEP DISORDER DETECTION

Accurate sleep staging is useful, but it is not the full clinical story. AI systems have also shown notable specificity in detecting the electrographic signatures of clinically distinct sleep disorders — a meaningfully harder task than staging alone. Three domains have received sustained and rigorous research attention.

5.1 PTSD and REM Sleep Disruption

Post-Traumatic Stress Disorder or PTSD affects 3.9 per cent of people all over the world. For people in the military who have seen combat, this number is much higher at over 20 per cent [25]. One of the problems people with PTSD have is trouble sleeping. [3] This is not a symptom; it is also a big part of what makes PTSD so bad. When people with PTSD sleep, their brain does not work the way it should. This is called REM sleep deregulation. It is a common problem people with PTSD have.[26],[2] A few things can go wrong with REM sleep in people with PTSD. These include:

- REM fragmentation, which means people wake up a lot during the night
- REM density, which means people move their eyes a lot while they sleep
- Altered theta coherence, which means the brain has trouble sending signals
- Attenuated frontal alpha activity, which means the brain is not as active as it should be

Scientists have discovered that when considering all of the above-mentioned factors together, they could diagnose a patient with post-traumatic stress disorder. Scientists were able to detect PTSD in patients using a computer-based brain wave analysis system with an accuracy of 88%. This is an improvement over other ways of diagnosing PTSD. This is not just important for diagnosing PTSD. It can also help doctors treat the disorder.

5.2 Obstructive Sleep Apnea

Sleep Apnea is another sleep disorder. It happens when the airway collapses during sleep, which can cause people to wake up a lot. [28] Doctors can use a test to see if someone has this disorder. Additionally, they may use a computer application to analyse the patient's brainwaves and determine if they suffer from the condition. [29] This might facilitate easy diagnosis and treatment at home.

5.3 Insomnia and Narcolepsy

Insomnia is a disorder affecting 10 to 15 per cent of adults. It is not merely a matter of lacking sleep but rather hyper arousal. Doctors can use a computer program to look at people’s brain waves and see if they have insomnia. They can also use the program to see what type of insomnia someone has, which can help them decide how to treat it. Narcolepsy is a disorder that affects some people [30]. It can cause them to be very sleepy during the day. Have trouble sleeping at night. Doctors can use a computer program to look at people’s brain waves and see if they have narcolepsy. This can be especially helpful because many people with narcolepsy do not get diagnosed for a time [31]. Post-Traumatic Stress Disorder or PTSD and these other sleep disorders are all very serious. With the help of computer programs doctors may be able to diagnose and treat them better. This could make a difference, in the lives of people with these disorders. PTSD and other sleep disorders are not something people have to live with they can be treated. With the help of computer programs doctors may be able to treat them even better.

VI. WEARABLE DEVICES AND LONGITUDINAL SLEEP MONITORING

Sleep analysis has become really good because of electronics, energy-efficient wireless transmission and artificial intelligence that works on devices. Wearable EEG platforms like forehead-mounted dry-electrode headbands, in-ear EEG systems and smart watches that combine accelerometric sensors can now capture good quality signals for reliable automated sleep staging [32]. The difference between consumer and clinical signal quality is still there. It is getting smaller. This has implications for clinical practice and research. Traditional sleep studies only capture one night of sleep. That night is not even a good representation of normal sleep because people sleep poorly in unfamiliar laboratory environments. Longitudinal wearable monitoring over weeks or months can capture how sleep varies from one person to another and how sleep disorders progress over time. These are things that a single-night study cannot do [33]. Artificial intelligence algorithms that work with devices have to deal with lower-quality signals, fewer electrodes and motion artefacts that are not a problem in laboratory recordings. One way to solve this problem is to use transfer learning: models that are trained on high-quality laboratory data are fine-tuned on wearable signals, which helps to transfer what the model has learned to the new type of signal [34]. Using information such as the degree of physical activity, the variations in heart rate, and the level of exposure to light can also enhance the accuracy of sleep staging where the EEG signals are not necessarily of good quality.

ISSN: 2581-9429
Volume 6, Issue 3, July 2026
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VII. CLINICAL APPLICATIONS AND FUTURE DIRECTION

7.1 Precision Sleep Medicine

Artificial intelligence is helping to change the way we think about sleep analysis from categorizing sleep disorders to really understanding each person's sleep health. By using algorithms on large databases of sleep phenotypes, researchers have found different subtypes of insomnia, sleep apnea, and depression-related sleep disturbances. Each with its own biological mechanisms and responses to treatment [35]. This level of detail cannot be achieved by analysis, and it creates a foundation for precision sleep medicine, where patients are matched to therapies based on their specific neurophysiological profile rather than just being given a diagnosis.

7.2 Real-Time Adaptive Sleep Systems

A new area of research involves closed-loop intelligence systems that do not just observe sleep but interact with it. For example, slow-oscillation entrainment is used, which is like a special kind of pink noise that is delivered at the right time to help improve the quality of deep sleep and memory consolidation [36]. On-device artificial intelligence that can analyse EEG signals in time enables the precise timing that these interventions require, turning passive monitoring devices into active tools for improving sleep.

7.3 Digital Biomarker Discovery

Analyzing databases of sleep EEG signals using artificial intelligence is also helping to discover new biomarkers for diseases. Researchers have found EEG signatures of neurodegeneration, including patterns associated with Alzheimer's and Parkinsons disease, as well as markers of cardiovascular and metabolic risk in sleep recordings years before clinical symptoms appear [37]. This could make artificial intelligence-analysed sleep EEG a useful tool for detecting diseases before symptoms appear.

7.4 Explainable AI (XAI) in Sleep Medicine

For intelligence to be used in clinical practice, it needs to be more than just accurate. Clinicians need to understand how it works and be able to trust it. Explainable artificial intelligence techniques, like SHAP values and saliency maps, can help clinicians see which EEG features and time intervals are most important for each classification, and this transparency is essential for building trust and meeting requirements [38].

VIII. ETHICAL, REGULATORY, AND PRACTICAL CHALLENGES

The performance of AI systems that analyse sleep is really good. That does not mean we should use them in clinics right away.

8.1 Data Privacy and Security

When we talk about sleep data, we are talking about personal information. This data can show us a lot about a person's health. That can be a problem if it gets into the wrong hands. It can also show us things like when a person sleeps and how well they sleep, and that information can be used against them. Most devices that people wear to track their sleep are not protected by the laws that protect medical information, and that is a big problem. One way to solve this problem is to use something called learning, where AI systems can learn from data without actually seeing the data itself [39].

8.2 Algorithmic Bias and Fairness

The people who are used to train AI systems are mostly white, adult, male and from North America. People from different backgrounds have different brain signals, and that means that AI systems may not work as well for them. If we do not make sure that our AI systems are fair, they may actually make health problems worse for some people. We need to make sure that our training data includes people from all backgrounds and that we test our systems to make sure they are fair [40].

8.3 Clinical Integration and Regulatory Approval

The rules for using AI systems to diagnose sleep problems are different in countries, and they are different depending on how the system is going to be used. In the US, the Food and Drug Administration (FDA) stated that some AI algorithms behave like medical devices and thus should be cleared for use in healthcare organizations. Even after being cleared for use, continued surveillance should be done to ensure that the AI algorithm is performing optimally [41]. This cannot be ignored because changes will occur over time that may impact the functionality of the AI algorithm.

8.4 Human-AI Collaboration

AI systems are not to replace doctors, to help them, AI systems are good at looking at a lot of data and finding patterns. Doctors are good at understanding the context and making decisions. The best way to use AI systems is to have them look at the data first and then have a doctor review the results and make a decision. This way we can make sure that we are using AI systems in a way that's responsible and fair. AI sleep analysis systems and doctors work well together. That is how we should use them in clinics. AI sleep analysis systems can help doctors by doing the screening, and then the doctors can look at the results and make a decision. This is the way to use AI sleep analysis systems in sleep medicine [38].

IX. CONCLUSION

Artificial Intelligence has changed the way we analyze sleep. This change is not minimal. We used to do sleep analysis by hand. It was subjective, meaning it was depended on the person doing it. We also only looked at one night of sleep at a time. Now we have automated systems that can look at sleep over a period of time and give us individualized information about each person's sleep health. This is a deal because it means we can help a lot of people at the same time. Artificial Intelligence tools like Transformer-based architectures and hybrid CNN-LSTM networks are very good at figuring out what is going on with a person's sleep. They are even better than experts in some cases. We can also use these tools with devices; that is, we can track people's sleep outside of a lab. This is helpful for people with sleep disorders like PTSD and insomnia. Sleep apnea. Artificial Intelligence is not a way to make sleep analysis more efficient. It is a new way of doing things. It allows us to help a lot of people at the same time while still giving each person individualized attention. This is something that we could not do before. Whether or not we use Artificial Intelligence in a way is up to us. We have the technology now; we just need to use it. We need people from fields to work together to make sure that Artificial Intelligence is used in a good way. This includes engineers, sleep specialists, neuroscientists, ethicists and regulatory authorities. If we work together, we can make sure that Artificial Intelligence helps people with sleep disorders rather than hurting them. AI is a technology that needs to be used wisely. AI can do much for understanding sleep and sleep disorders. It must be utilized in a way that will benefit humans.

X. ACKNOWLEDGMENT

The authors sincerely thank **AISSMS Institute of Information Technology, Pune**, for providing the support and facilities required to carry out this research work. The authors also acknowledge the valuable guidance and encouragement received from colleagues and well-wishers throughout the study.

FUNDING INFORMATION: There is no funding for this review.

CONFLICT OF INTEREST STATEMENT: The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT: The data used to support the findings of this study are available from the corresponding author's research article, citation is given in the review paper.

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