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AI-DRIVEN WEARABLE HRV MONITORING FOR EARLY DETECTION OF NURSE FATIGUE AND ITS IMPACT ON CLINICAL PERFORMANCE AND PATIENT SAFETY: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT
Nurse fatigue is a major occupational health concern that negatively affects clinical performance, recovery, and patient safety. Prolonged working hours, night shifts, and job-related stress disrupt autonomic balance and increase the likelihood of clinical errors. Heart Rate Variability (HRV) has been widely recognised as a sensitive physiological biomarker of fatigue and occupational stress. Integrating Artificial Intelligence (AI) with HRV-enabled wearable technology offers a promising approach for real-time and objective fatigue monitoring in nursing populations. This systematic literature review aimed to synthesise evidence on AI-enhanced HRV wearable technology for early detection and management of nurse fatigue. The review followed PRISMA guidelines and was registered in PROSPERO (CRD420251251457). Searches were conducted across six electronic databases (Scopus, ProQuest, ScienceDirect, SAGE, Wiley, and SpringerLink) using predefined Boolean keywords, including “wearable device”, “wearable technology”, “smartwatch”, “heart rate variability”, “artificial intelligence”, “machine learning”, “nurse*”, “nursing practice”, “fatigue”, and “clinical decision support”*. Articles published in English between 2015 and 2025 were included. From 1,689 records identified, 11 studies met the inclusion criteria after screening and methodological quality appraisal using Joanna Briggs Institute tools. AI-integrated wearable systems demonstrated high diagnostic performance, with fatigue detection accuracy around 80% for machine learning models and exceeding 99% for multimodal biosensing systems. Physiological biomarkers—including HRV, cortisol, electrodermal activity, and skin temperature—consistently reflected objective fatigue, particularly during extended working hours. Intervention studies showed that AI-supported HRV biofeedback and cognitive behavioural approaches improved autonomic regulation and nurse wellbeing. AI-enabled HRV wearable technology represents a feasible and promising strategy for early fatigue detection and wellbeing optimisation among nurses, with potential benefits for clinical performance and patient safety. However, practical implementation and long-term integration into healthcare systems remain key considerations for future research.

Keywords: artificial intelligence; biofeedback; heart rate variability; nurse fatigue; wearable technology

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INTRODUCTION

Nurse fatigue is known to represent a perpetual threat for patient safety and nurse decision-making and sustainability. Activities performed by the nurse that cause potential physiological and psychological strains are related to shift schedules and high-intensity environments that impair autonomic function and cognitive function(Jelmini et al., 2023; Leso et al., 2021) . Recent evidence shows that nurse fatigue is strongly related to HRV and is considered a sensitive biomarker of autonomic balance imbalance that is influenced by workload and stress and disruption of internal rhythms (Ahmadi et al., 2021; Penfold et al., 2025; Shen et al., 2025; Zhan et al., 2025). Thus, the growing need for objecti ve and real-time nurse fatigue analysis tools has become particularly urgent (Zeng et al., 2024).

Wearable physiological sensors also provide a promising approach by allowing the adherent and unobtrusive monitoring of HRV in real-world clinical environments (Review & Raines, 2024). Validation research has shown the accuracy of photoplethysmography-based HRV measurements comparable to those of electrocardiography and validated the usability of such devices for shift-different monitoring in nursing practice (X. Li et al., 2022). Moreover, observational evidence also indicates a subsequent worsening of HRV after night shift work and high workloads indicating autonomic fatigue over time (Ahmadi et al., 2021; Liu et al., 2023; Zhan et al., 2025). At the organizational level, too high workloads have also shown a negative effect on ICU productivity, suggesting post-fatigue implications regarding work behavior and performance (Park et al., 2022).

The integration of artificial intelligence (AI), specifically machine learning, has significantly improved the accuracy of nurse fatigue recognition using wearable technology. HRV-based predictive models have shown classification accuracies of well above 80% for hospital nursing personnel (Hafiz et al., 2025; Kim et al., 2025; Liu et al., 2023), whereas highly complex models that incorporate HRV features along with neurophysiological signals have recorded nearly perfect results in shift working settings (Wang et al., 2025). Such results confirm the capability of AI-assisted wearables to simplify complex physiological signals into meaningful information (Sharma et al., 2025). The emerging intervention studies also confirm the relevance of HRV-related approaches. HRV biofeedback has been demonstrated to promote healthy autonomic function in nursing personnel (Macedo et al., 2023) as well as increase resilience and stress in health care workers using mobile applications (Mensinger et al., 2024). Overall, the current findings indicate that HRV regulation in a wearable technology-assisted manner is a practical and reproducible approach (Li et al., 2023).

Although there has been growing evidence, the current body of studies has been fragmented in terms of focusing either on detection, predictions, or interventions independently (Raj & Sapra, 2026). Also, there has been no convergent synthesis of different aspects of using HRV biomarkers, wearables, and AI analytics, and thus this current review systematically reviews evidence regarding AI-driven HRV wearables for detection and management of nurse fatigue, conceptualizing it as a dynamic and modifiable phenomenon and lays a foundation for future nursing practices and patient safety interventions accordingly (Hafiz et al., 2025).

The current research is still dispersed, despite the fact that studies have shown that heart rate variability (HRV) is a reliable objective biomarker of nurse exhaustion and that AI-enhanced HRV devices have promising detection accuracy. The majority of research focusses on detection, prediction, or intervention separately, with little integration of wearable technology, artificial intelligence, and HRV biomarkers within a cohesive conceptual framework(Adão Martins et al., 2021). Additionally, longitudinal knowledge of fatigue trajectories and their consequences for clinical performance and patient safety is limited by the prevalence of observational and cross-sectional machine-learning designs. The need for a more comprehensive systematic synthesis is further highlighted by the lack of strong interventional data and its restricted generalisability (Imran et al., 2024). This review aims to synthesize current evidence on AI-enabled wearable heart rate variability monitoring for nurse fatigue detection, focusing on diagnostic performance, physiological biomarkers, and implications for early intervention and workforce well-being.

METHOD

Desain studi

This study used the systematic literature review technique to combine all the evidence that currently exists about the application of heart rate variability (HRV)-supported wearable technology and artificial intelligence (AI) for the detection and prevention of fatigue in nurses. The protocol for conducting this study is registered on the PROSPERO register (CRD420251251457). This systematic literature review was carried out following the Preferred Reporting Items for Systematic

Reviews and Meta-analyses guidelines. The databases used for the review include Scopus, SAGE, Wiley, ScienceDirect, ProQuest, and the Springer database.

Out of 1,689 records obtained from the database search, 1,369 articles were excluded on the basis of the initial limiting criteria. The remaining 320 articles were selected on the basis of the title and abstract. This shortlisted 70 articles, of which 20 articles were selected on the basis of the full-text analysis. Finally, 11 articles were selected on the basis of the quality of the methodological approach as depicted in Figure 1.

The search and inclusion were limited to full-text articles accessible through open access and publishing only in the English language between 2015 and 2025. The process of data gathering involved six steps: (1) entering keywords into the search engines of the database; (2) inclusion criteria; (3) downloading and organizing articles using citation management software; (4) screening the titles and abstracts; (5) evaluation of full-text articles; and finally, (6) evaluation of methodological quality. The inclusion criteria were applied for selecting articles using the PECOS criteria (Table 1). Editorials, narrative reviews, research proposals, and studies which neither applied HRV-based wearable technology nor targeted nursing populations were excluded from the review.

Table 1.
PECOS Framework

PECOS Component	Inclusion Criteria
Population	Nurses or healthcare professionals with a predominance of nurses
Exposure	Use of HRV-measuring wearable devices, with or without artificial intelligence or machine learning algorithms
Comparator	No comparator or baseline condition (e.g. pre-shift or usual condition)
Outcome	Occupational fatigue, workload, physiological indicators of fatigue, clinical performance, or patient safety
Study Design	Experimental

The article search was conducted systematically across the electronic databases Scopus, ProQuest, ScienceDirect, SAGE, Wiley Online Library, and SpringerLink. Keywords were combined using Boolean operators as follows:
("wearable device*" OR "smart device*" OR "wearable sensor*" OR "smartwatch*" OR "wearable technology") AND ("clinical decision-making" OR "clinical decision support" OR "decision support system" OR "nursing judgment") AND ("nursing practice" OR "nursing care" OR "nurse*" OR "clinical nurse")

RESULT

Searches in the databases resulted in 1,689 articles: 1,330 from ProQuest, 28 from Scopus, 54 from SAGE, 137 from Wiley Online Library, 50 from ScienceDirect, and 90 from SpringerLink. A total of 1,369 articles were excluded for failing to meet the basic criteria, such as limited full-text access or not being relevant to the topic. Of those, 320 proceeded to preliminary screening, in which titles and abstracts were reviewed. At this point, 250 were excluded due to not focusing on HRV-based wearable technologies, not using artificial intelligence or machine learning in analyzing data, not investigating fatigue, or investigating populations other than nurses. The remaining 70 articles went on to full-text review.

During the full-text eligibility check, 50 articles were excluded due to the type of wearable not being for fatigue monitoring, the absence of outcomes on clinical performance and patient safety, or due to the restriction on access to the full text despite being tagged as open access. A total number of 20 articles met the initial stage of eligibility and thus proceeded to undergo methodological quality appraisal using the Joanna Briggs Institute Critical Appraisal Tools. Following the methodological quality appraisal, nine articles were subsequently excluded with low methodological quality, while the remaining 11 studies were eventually considered in this review (see Figure 2).

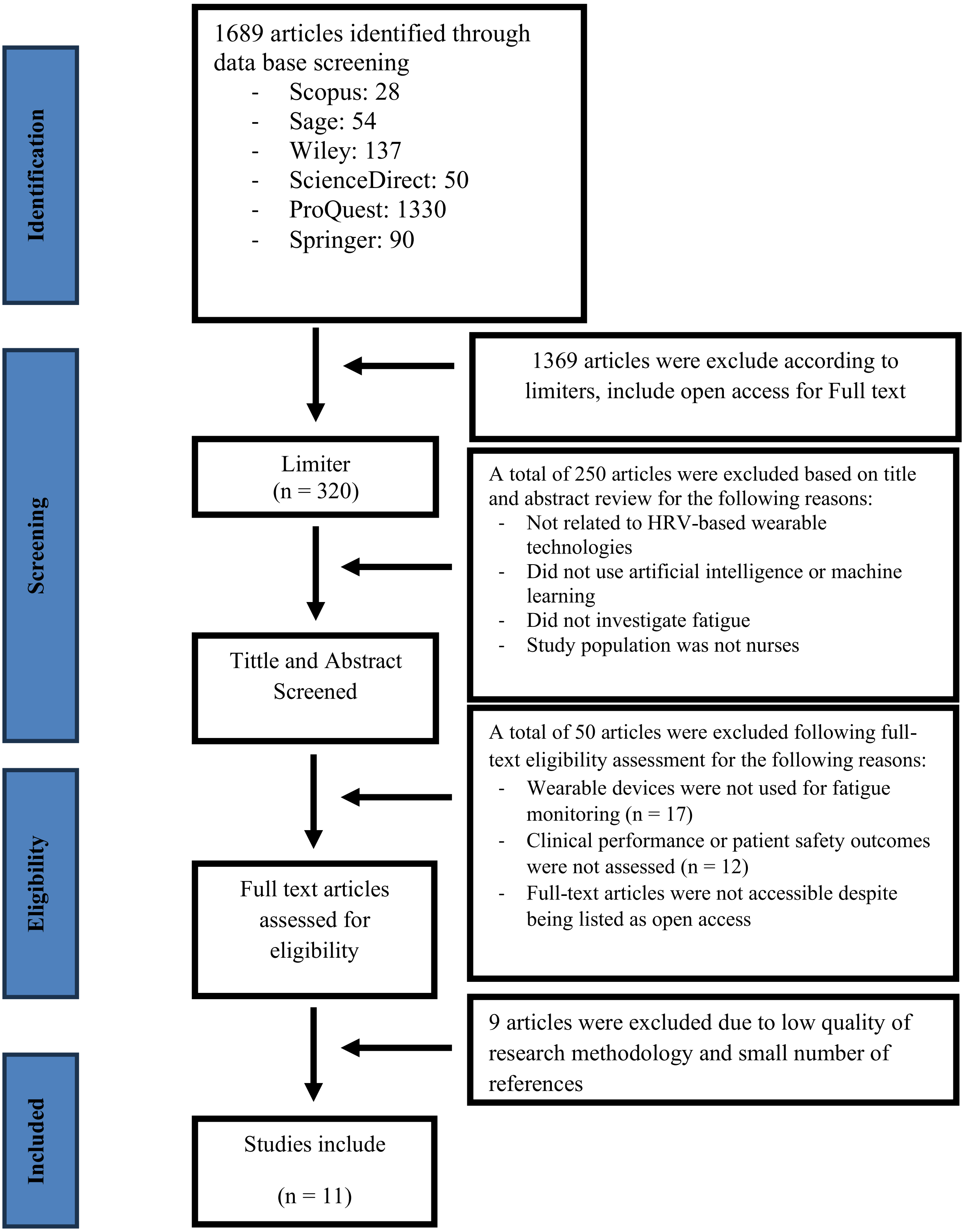

Figure 1. PRISMA Diagram

Reviewing these 11 studies revealed the following key themes. First, there was a focus on early detection of clinical fatigue using HRV-based wearables linked with artificial intelligence, with several studies reporting high predictive accuracy. Second, HRV and other physiological biomarkers were objective fatigue indicators for nurses, including postshift HRV reductions and autonomic nervous system responses to workload. Third, wearable-based digital interventions, such as HRV biofeedback and self-monitoring apps, were noted to reduce fatigue and improve the wellbeing of nurses. Fourth, the research highlighted how fatigue impairs clinical performance and patient safety, and the challenges of integrating wearable-AI solutions into healthcare systems.These studies ranged across several countries, with most coming from Asia and North America. Most of the studies utilized observational designs and developed machine-learning models, followed by experimental and quasi-experimental approaches. Overall, these findings suggest that HRV-based wearables combined with AI represent a fast-evolving approach in nursing practice and occupational health and safety.

Table 2.
Data Extraction Results

Study	Country Setting	Design and Sample	Population	Intervention or Exposure	Comparator	Outcomes	Key Findings	Appraisal	Notes
Liu 2023	Taiwan Emergency Departement	Prospective machine learning n110	Emergency staff mostly nurses	Smartwatch HRV with machine learning	None	HRV and fatigue scale	High accuracy fatigue prediction	High	Strong evidence for AI wearable fatigue detection
Hafiz 2025	Indonesia Hospital	Machine learning development n60	Shift nurses	HRV classifier using chest strap	Algorithm comparison	HRV and accuracy	Good fatigue classification accuracy	Good	Relevant to Indonesian nursing context
Ito Masui 2023	Japan ICU and ED	Single arm trial n61	Nurses and physicians	AI CBT sleep app with wearable	None	Sleep quality burnout	Improved sleep duration	Moderate	Indirect fatigue relevance
Wang 2025	China Anaesthesia unit	Experimental controlled	Anaesthesiologists	EEG and HRV wearable with AI	Pre shift baseline	HRV EEG cognition	Very high fatigue detection accuracy	High	Strong physiological model
Kim 2025	Korea Hospital	Cross sectional and ML n336	Shift nurses	HRV and cortisol pre post shift	Shift type	HRV cortisol fatigue	Significant HRV fatigue association	Moderate High	Large nursing sample
Zhan 2025	China Tertiary hospital	Longitudinal observational	Night shift nurses	Night shift workload	Day comparison	HRV physical capacity	HRV declined after night shift	High	Strong temporal evidence
Li 2022	United States	Pilot validation	Nurses	Wearable PPG compared to ECG	ECG reference	HRV accuracy	Wearable valid for HRV monitoring	High	Important validation study
Park 2022	United States ICU	Longitudinal EMR analysis	ICU care teams	ICU workload census	Capacity level	Clinical productivity	Productivity declined with overload	High	System level fatigue proxy
Ahmadi 2021	United States ICU	Longitudinal shift study n23	ICU nurses	Real workload exposure	Within shift	HR EDA skin temperature	Physiological stress response observed	High	High ecological validity
Macedo 2023	Brazil Hospital	Randomised controlled trial n115	Nursing staff	HRV biofeedback training	Sham control	HRV stress outcomes	Improved autonomic regulation	High	Strong intervention evidence
Mensinger 2024	United States Multi site	Pilot feasibility n23	Healthcare workers mostly nurses	Mobile HRV biofeedback app	Baseline comparison	HRV stress resilience	Improved wellbeing indicators	Moderate	Scalable wearable intervention

A total of ten empirical studies met the inclusion criteria, encompassing observational cohort studies, machine-learning-based cross-sectional studies, diagnostic accuracy research, quasi-experimental designs, and randomised controlled trials. Sample sizes ranged from 20 to 336 participants, with most studies involving shift-working nurses in emergency departments, intensive care units, and general hospital wards.

Objective HRV Changes Associated with Shift Work and Workload

Four observational cohort studies consistently demonstrated that HRV decreases with increasing workload, night shifts, and cumulative fatigue. Zhan et al., (2025) reported reductions in RMSSD and high-frequency power following night shifts, with progressively impaired autonomic recovery on subsequent days. Ahmadi et al., (2021) identified significant correlations between heart rate, electrodermal activity, and skin temperature with perceived stress during 12-hour ICU shifts. Park et al., (2022) identified specific workload thresholds associated with declines in ICU productivity, reflecting accumulated fatigue at the system level. Liu et al., (2023) observed strong associations between HRV indices and subjective fatigue scores among emergency healthcare workers.

Diagnostic Accuracy and Feasibility of HRV Wearable Devices Li et al., (2023) demonstrated high diagnostic agreement between photoplethysmography-based wearable devices and electrocardiography-derived HRV measures, confirming the feasibility of PPG technology for real-time fatigue monitoring. This validation supports the use of consumer-grade or chest-strap wearables for shift-based monitoring in nursing populations.

Machine Learning Approaches to Fatigue Prediction

Several studies employed machine learning techniques to enhance the predictive capacity of physiological signals. Kim et al., (2025) and Hafiz et al., (2025) achieved fatigue classification accuracies of approximately 81 per cent using HRV as the primary predictor. Liu et al. (2023) reported comparable performance with an area under the curve of 0.838. Wang et al., (2025) demonstrated near-perfect accuracy (99.4 per cent) through the integration of EEG and HRV signals.

Interventions to Improve Autonomic Regulation

Two intervention studies indicated that wearable devices may serve not only as monitoring tools but also as mechanisms to improve autonomic regulation. Macedo et al., (2023) found that cardiovascular biofeedback significantly improved HRV indices over a three-week intervention period. Similarly, Mensinger et al., (2024)reported improvements in interoceptive awareness, self-care behaviours, resilience, and stress outcomes following eight weeks of smartphone-based HRV biofeedback.

Table 3.
Effectiveness of Wearable Technologies for Monitoring Nurse Fatigue (Consolidated Evidence)

No	Wearable Category	Key Studies	Population	Physiological Parameters	Analytic Approach	Main Effectiveness Evidence	Level of Evidence	Overall Effectiveness
1	Smartwatch or wrist based HRV using PPG	Liu 2023 Kim 2025 Zhan 2024	Shift nurses and emergency nurses	Heart rate and HRV including RMSSD SDNN and high frequency power	Machine learning and longitudinal analysis	Accurate fatigue prediction and consistent reduction of HRV after night shifts	Moderate to high based on cohort and machine learning studies	High and most practical
2	Chest strap HRV clinical grade devices	Hafiz 2025 Li 2022	Shift nurses	HRV time and frequency domain measures	Machine learning and diagnostic validation against ECG	Good fatigue classification and strong agreement with ECG	High based on validation and modelling studies	High with best signal quality
3	Multimodal wearable combining EEG and HRV	Wang 2025	Clinicians during long shifts	EEG and HRV parameters	Machine learning with transfer learning	Very high accuracy in fatigue classification across individuals	High based on experimental study	Very high but limited feasibility
4	Wearable HRV biofeedback systems	Macedo 2023 Mensinger 2024	Nurses and healthcare workers	HRV coherence and RMSSD	Randomised trial and pre post intervention	Improved autonomic regulation reduced stress and increased resilience	Moderate to high based on trial and pilot studies	High for intervention use

No	Wearable Category	Key Studies	Population	Physiological Parameters	Analytic Approach	Main Effectiveness Evidence	Level of Evidence	Overall Effectiveness
5	Consumer wearables with sleep or wellbeing applications	Ito Masui 2023	Shift working nurses and physicians	Sleep duration and HRV proxy measures	Single arm intervention study	Increased sleep duration and reduced burnout	Moderate	Moderate with indirect fatigue effects
6	Multi sensor physiological monitoring without dominant HRV	Ahmadi 2022	Intensive care nurses	Heart rate electrodermal activity and skin temperature	Observational correlation analysis	Clear associations between workload and physiological stress responses	Moderate	Moderate

Interpretation of Effectiveness

According to the study, there is considerable variation in how usable wearable technology is in terms of measuring fatigue among the nursing profession. Cardiovascular variability devices that utilize the photoplethysmography method on the wrist provide the optimal trade-off among the three mentioned aspects, since these devices are fairly accurate from a physiological standpoint, fatigue prediction is fairly accurate, and they are usable in a real-world nursing capacity. The chest-strap HRV devices provide better signal quality, and they correlate well with the ECG. Those devices are good for testing, as they pose certain comfort problems that do not allow usage in real-life conditions. The combination of the EEG and the HRV produces high accuracy but is too complicated and invasive. HRV biofeedback devices are more suited as intervention devices, where they help in enhancing resilience and self-care, whereas the use of HRV devices as monitors has limited benefits. Consumer devices with sleep and wellbeing applications could offer moderate benefits, and a multi-sensor system that is not HRV dominant does not offer enough information for diagnosing fatigue on its own. In conclusion, the evidence supports wrist-worn HRV measurement and enhancement with machine learning as the best pragmatic pathway for the early detection of nurse fatigue with HRV biofeedback Interventions to improve nursing staff recovery and resilience.

DISCUSSION

This systematic review combines findings on employing HRV-enabled wearable devices in conjunction with artificial intelligence solutions for detecting and managing nurse fatigue. Findings suggest cumulative evidence demonstrating heart rate variability data gathered using wearable devices offers a valid, objective, and meaningful indicator of nurse fatigue associated with shift work schedules, workload, and cumulative physiological stresses among nursing professionals. HRV Wearables as Objective Indicators of Nurse Fatigue. Various studies-snapshots and longer-term follow-ups alike-the heart-rate variability signal tends to decrease when nurses are working night shifts, working longer hours, or having a heavier workload. This would reflect sensitivity of HRV to autonomic imbalance. Time- and frequency-domain measures are lower on such occasions; for example, RMSSD and high-frequency power indicate lesser parasympathetic activity and slower recovery processes after stressful shifts (Ahmadi et al., 2021; Zhan et al., 2025). In conclusion, physiological monitoring provides significant added value to the assessment of fatigue because it completes self-reported measures that might be susceptible to response bias, professional norms, or symptom unawareness.

Crucially, studies show strong agreement between wearables using photoplethysmography and HRV derived from ECG (Li et al., 2022) underlining that the introduction of wearable technology into everyday nursing practice is possible. This validation supports the use of either consumer- or clinically oriented wearables for continuous, non-invasive fatigue tracking in real-world healthcare settings. Added Value of Machine Learning for Fatigue Detection. Added Value of Machine Learning on Fatigue Detection. The use of machine learning brings a significant improvement in interpretability and use of wearable-derived physiological measures. A number of researchers have shown that machine learning algorithms using HRV can classify nurse fatigue with accuracy above

80 percent (Hafiz et al., 2025; Kim et al., 2025; Liu et al., 2023). It is thus evident that AI-driven analysis can use autonomic measures in a way that is useful in a real-world medical setting, predicting nurse fatigue before a performance decrease. Though the multimodal technique coupling HRV with EEG has a near-perfect rate of classification accuracy (Wang et al., 2025), the poor feasibility of these techniques in real-world clinical settings limits their usefulness. On the other hand, HRV devices based on the wrist and using machine learning techniques offer the most realistic trade-off with respect to accuracy and feasibility.

Implications for Occupational Health and Patient Safety. The observed association between workload, autonomic strain, and reduced clinical productivity highlights the broader system-level implications of nurse fatigue. Evidence that intensive care unit performance declines under excessive workload conditions (Park et al., 2022) aligns with physiological findings of autonomic depletion, suggesting that HRV monitoring may function as an early warning indicator for staffing adequacy, shift design, and patient safety risk. Integrating HRV data into occupational health surveillance systems could therefore support proactive fatigue management strategies rather than reactive responses to adverse events.

HRV Biofeedback as a Fatigue Mitigation Strategy. Beyond monitoring, this review highlights the therapeutic potential of wearable-assisted HRV biofeedback. Randomised and pilot studies demonstrate that biofeedback interventions can improve autonomic regulation, resilience, and self-care behaviours among nursing staff (Macedo et al., 2023; Mensinger et al., 2024). Although subjective stress reduction was not always pronounced, improvements in physiological regulation suggest meaningful recovery benefits. These findings position HRV biofeedback as a complementary intervention that may be deployed alongside monitoring systems to support fatigue recovery and long-term workforce wellbeing.

Research Gaps and Future Directions. Despite promising evidence, several limitations persist in the current literature. First, many machine-learning studies employ cross-sectional designs, limiting causal inference and temporal modelling of fatigue trajectories. Second, observational studies often lack adequate control for confounding factors such as sleep quality, caffeine intake, or baseline fitness. Third, most studies are single-centre with modest sample sizes, constraining generalisability. Finally, only a small number of interventional trials are available, underscoring the need for robust randomised controlled trials.

Future research should prioritise longitudinal validation of wearable–AI fatigue systems, integration with hospital information infrastructures, and evaluation of cost-effectiveness, particularly in low- and middle-income healthcare settings. The development of real-time fatigue alert systems linked to staffing and workflow decisions represents a critical next step. Overall Implications. Taken together, the evidence supports wearable HRV monitoring enhanced by machine learning as a feasible, accurate, and clinically relevant approach to nurse fatigue surveillance. When combined with biofeedback-based interventions, these technologies offer a comprehensive framework for early detection, recovery support, and resilience enhancement. Such an approach has the potential to improve workforce wellbeing, reduce fatigue-related errors, and strengthen patient safety in contemporary healthcare systems.

CONCLUSION

Overall, the evidence indicates that HRV-based wearable technologies represent a feasible, accurate, and clinically relevant approach for monitoring nurse fatigue. When enhanced with artificial intelligence and biofeedback interventions, these technologies offer substantial potential to support early fatigue detection, promote autonomic recovery, improve workforce wellbeing, and enhance patient safety. Future research should focus on longitudinal validation, integration with hospital digital systems, and the evaluation of real-time fatigue monitoring frameworks in routine clinical practice.

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