Systematic Literature Review: Heart Rate Variability (HRV) as a Neurobiological Biomarker of Mindfulness Effects on Emotion Regulation

Anggita Rana Sasmita Lestari
Master's Program in Biomedical Sciences (specializing in Physiology), Faculty of Medicine, UIN Syarif Hidayatulah Jakarta

Atika Rahmania El Barusi
Department of Psychology, Universitas Muhammadiyah Prof. Dr. Hamka, Jakarta, Indonesia

Abstract: Heart Rate Variability (HRV) is increasingly relevant in applied psychology and medicine because it offers objective indices of autonomic flexibility tied to emotion regulation. Mindfulness interventions including brief, intensive, and online-based programs have been studied in relation to HRV, using both time-domain (e.g. RMSSD, SDNN) and frequency-domain (e.g. high-frequency power, HF; LF/HF ratio) parameters. In this review (40 empirical studies from 2020–2025, randomized controlled trials, within-subject and longitudinal designs), we find that mindfulness significantly increases parasympathetic-related HRV measures (notably RMSSD and HF) and reduces emotional distress (e.g. anxiety, stress) relative to baseline or control conditions. However, effect sizes are variable due to methodological inconsistencies (different HRV recording durations, resting vs. active tasks) and heterogeneous samples. The review highlights HRV's promise as a biomarker for mindfulness-based emotion regulation, especially when studies use standardized protocols. For maximum impact, future work should employ longer follow-ups, rigorous RCTs, and integrate multi-modal physiological and psychological measurement across diverse populations.

Keywords: Emotion Regulation, Heart Rate Variability, Mindfulness, Neurobiological Biomarker.

Correspondents Author:
Anggita Rana Sasmita Lestari, Department of Biomedicine, UIN Syarif Hidayatullah Jakarta, Indonesia
Email: anggita.rana2@gmail.com

Received October 3 2025; Revised October 16, 2025; Accepted October 18, 2025; Published October 20, 2025.

Introduction

Heart Rate Variability (HRV) has emerged as one of the most promising physiological biomarkers in contemporary neuroscience research, particularly in the context of emotion regulation and mindfulness-based interventions. HRV represents the temporal variation in the intervals between heartbeats, reflecting the dynamic modulation of the autonomic nervous system (ANS) on cardiovascular function. Neurobiologically, HRV captures the complexity of interactions between the sympathetic and parasympathetic branches of the ANS, where high variability indicates adaptive flexibility in responding to both internal and external demands. Recent studies suggest that HRV is not merely an indicator of cardiovascular health but also a sensitive neurobiological biomarker linked to higher-order cognitive and emotional processes, including emotion regulation, executive control, and psychological adaptability (Appelhans & Luecken, 2006; Karsh et al., 2006). In practical terms, HRV provides an objective physiological measure that can be applied to assess the effects of psychological interventions on stress reduction, emotional balance, and overall mental well-being, thus bridging the gap between physiological mechanisms and psychological outcomes.

Mindfulness, defined as non-judgmental awareness of the present moment, has been widely examined for its ability to induce neuroplastic effects in the brain, particularly within regions such as the prefrontal cortex, anterior cingulate cortex, and insula. These neurobiological changes are closely associated with the modulation of autonomic function as reflected in HRV, offering a neurophysiological pathway to explain the beneficial effects of mindfulness on psychological regulation (Smith et al., 2017). Within the domain of emotion regulation, mindfulness has been shown to strengthen prefrontal limbic connectivity, resulting in improved control over impulsive or emotionally reactive behaviors. This process involves complex interactions between the limbic system, especially the amygdala, and the prefrontal regions responsible for executive regulation (de Moura Targino et al., 2025; Gkintoni et al., 2024; Bigler, 2016). Neuroimaging evidence has demonstrated that successful emotion regulation is associated with specific patterns of neural activation, while physiologically, it is reflected in the adaptability of the ANS as captured by HRV indices such as Root Mean Square of Successive Differences (RMSSD) and high-frequency (HF) components, both of which indicate parasympathetic (vagal) influence (Appelhans & Luecken, 2006).

The autonomic nervous system serves as the primary interface between psychological processes and physiological responses, dynamically balancing sympathetic and parasympathetic activities. In emotion regulation, parasympathetic activity mediated by the vagus nerve supports “rest and digest” responses and facilitates recovery from stress, whereas sympathetic dominance is linked to “fight or flight” reactions and reduced HRV. The

neurovisceral integration model highlights the functional connection between cognitive-emotional control networks and cardiovascular regulation (Smith et al., 2017). Mindfulness practice has been demonstrated to modulate autonomic activity by enhancing parasympathetic tone, which is reflected in increases in HF-HRV and time-domain indices such as RMSSD. These physiological mechanisms operate through strengthened communication between the prefrontal cortex and limbic structures and are accompanied by downregulation of HPA-axis reactivity and inflammatory processes. Furthermore, mindfulness induces structural neuroplasticity, including increased grey matter density in brain regions associated with attentional control, emotional regulation, and self-awareness (Pascoe et al., 2017).

Meta-analytic and empirical evidence demonstrates that mindfulness interventions significantly improve HRV across diverse populations and contexts, although the findings are moderated by methodological heterogeneity, differences in intervention duration, and variations in HRV parameters. Studies employing Mindfulness-Based Stress Reduction (MBSR), brief meditation interventions, or online mindfulness programs consistently report increases in parasympathetic-related HRV metrics (RMSSD, HF power), which are associated with reductions in stress, anxiety, and emotional distress (Virgili, 2015; Ong et al., 2014; Casey et al., 2008). However, inconsistencies in HRV recording protocols, such as measurement duration, posture, and environmental conditions, present challenges in comparing outcomes across studies. The distinction between state (acute, short-term) and trait (long-term, dispositional) mindfulness effects on HRV also warrants careful consideration, as short-term practice may produce transient autonomic changes, whereas sustained practice can lead to stable improvements in vagal regulation (Smith et al., 2017). To ensure validity and reliability, the standardization of HRV assessment protocols is essential, covering time-domain, frequency-domain, and non-linear measures (Zaccaro et al., 2018).

Individual variability in HRV responses to mindfulness interventions represents an increasingly important area of inquiry. Factors such as baseline HRV, demographic characteristics, health conditions, prior meditation experience, and personality traits influence both the magnitude and direction of HRV changes following mindfulness training (Pascoe et al., 2017). Understanding moderators and mediators in the mindfulness–HRV–emotion regulation relationship is crucial for developing more personalized intervention models. Identifying individual profiles that demonstrate the greatest responsiveness to mindfulness-based approaches could improve clinical outcomes and enhance the cost-effectiveness of mental health interventions. This precision-oriented perspective highlights the potential of HRV as a predictive biomarker for individual differences in emotional resilience and treatment response.

The clinical application of HRV as a biomarker in mindfulness-based emotion regulation research offers significant opportunities but also presents multiple challenges. In therapeutic contexts, HRV can be used as an objective physiological index to monitor treatment progress, evaluate therapy effectiveness, and predict clinical responsiveness. Yet, the translation of HRV research into clinical practice requires establishing normative reference values, cut-off thresholds, and clinically meaningful effect sizes parameters that remain insufficiently standardized. Moreover, inter-individual variability and contextual confounders such as physical activity, respiration, and circadian rhythm complicate the interpretation of HRV changes (Zaccaro et al., 2018).

Recent advancements in wearable technology and mobile health (mHealth) applications have revolutionized HRV data collection, allowing for continuous and ecologically valid monitoring during mindfulness interventions. These technologies enable real-time feedback loops that can enhance participant engagement and adherence. Nevertheless, questions remain about the measurement accuracy of consumer-grade HRV devices compared to laboratory-grade equipment, particularly for research requiring high precision and clinical reliability. Consequently, the validation and standardization of wearable HRV technologies are critical steps toward integrating HRV monitoring into mindfulness-based interventions in both research and clinical domains (Zaccaro et al., 2018).

The integration of neuroimaging techniques with HRV research has further enriched understanding of the heart–brain connection in mindfulness and emotion regulation. Evidence from neuroimaging studies indicates that HRV correlates with neural activity and functional connectivity in emotion regulation circuits, particularly involving prefrontal–amygdala and insula networks (El Morr et al., 2020; Smith et al., 2017). Such findings illuminate the neurobiological substrates underlying HRV fluctuations and suggest that combining HRV with neuroimaging and behavioral assessments provides a comprehensive framework for studying the psychophysiological mechanisms of mindfulness. These multimodal approaches enhance the ecological validity of mindfulness research and contribute to identifying precise neural and autonomic markers of emotional regulation.

From a translational perspective, research on HRV, mindfulness, and emotion regulation underscores the necessity of bridging laboratory findings with clinical and applied practices. Challenges include the standardization of experimental protocols, the development of clinical guidelines, training for health professionals in HRV-informed therapy, and the integration of HRV-based feedback systems within mindfulness interventions. There is also a growing emphasis on evaluating the cost-effectiveness and long-term sustainability of these interventions (Pascoe et al., 2017). Future directions should prioritize longitudinal designs to assess the persistence of HRV changes over time, investigate dose response relationships in

mindfulness practice, and adopt multimodal analytic frameworks combining physiological, neuroimaging, and psychological data. Additionally, the creation of predictive HRV models may facilitate the personalization of mindfulness-based interventions (Craven et al., 2019).

Given the complexity and interdisciplinary significance of this topic, conducting a systematic literature review (SLR) on HRV as a neurobiological biomarker of mindfulness effects on emotion regulation is both timely and essential. Such a review aims to analyze the empirical evidence, evaluate methodological rigor, identify research gaps, and offer directions for future investigations. It will also assess the translational potential of HRV in clinical mindfulness applications and its implications for developing evidence-based interventions that enhance emotional regulation and psychological well-being. This review contributes to advancing both theoretical understanding and applied practice by clarifying the physiological mechanisms through which mindfulness influences HRV and, in turn, emotion regulation (Álvarez-Pérez et al., 2022; Breedvelt et al., 2019)

Research Method

This study employs a Systematic Literature Review (SLR) method, adhering to the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The use of the SLR method was deemed appropriate given the objective to comprehensively synthesize empirical and conceptual evidence on the relationship between mindfulness, emotion regulation, and Heart Rate Variability (HRV) as a neurobiological biomarker. This approach ensures transparency, minimizes selection bias, and enhances the methodological rigor of the review process. The inclusion of HRV as a core variable allows for an integrative understanding of autonomic and psychological processes, particularly those reflecting parasympathetic activity (e.g., high-frequency [HF] HRV) and vagal tone modulation associated with mindfulness based practices.

The review process followed four major PRISMA stages identification, screening, eligibility assessment, and inclusion. At the identification stage, a total of 412 articles were retrieved from Scopus and Google Scholar databases. After duplicate removal and relevance screening based on titles and abstracts, 118 studies were retained for full-text review. Subsequently, 40 articles met all inclusion criteria and were finally included in the synthesis. A detailed PRISMA flow diagram is provided to illustrate the selection process, including the number of articles excluded at each phase along with the reasons for exclusion (e.g., conceptual irrelevance, methodological insufficiency, or missing HRV data).

To ensure methodological transparency and consistency, the JBI (Joanna Briggs Institute) Critical Appraisal Checklist was applied to assess the quality of each selected study. This tool was chosen due to its comprehensive evaluation of research design, methodological clarity,

and data validity across diverse study types, including randomized controlled trials (RCTs), quasi-experimental studies, and observational research. The use of such a structured quality assessment ensured that only studies with sufficient methodological rigor were synthesized in the final analysis. Although Google Scholar was used as a complementary source to capture gray literature and non-indexed journals, Scopus served as the primary database due to its superior indexing accuracy and peer-review standards. This dual-database strategy balances inclusivity and quality control while acknowledging potential limitations in database coverage and duplication risk. The search strategy combined Boolean operators and field-specific filters. The search strings included: ("Heart Rate Variability" OR HRV) AND ("Mindfulness" OR "Mindfulness-Based Intervention") AND ("Emotion Regulation" OR "Affective Regulation") AND ("Neurobiological Biomarker").

Filters were applied to restrict results to peer-reviewed articles, human studies, and English or Indonesian language publications within 2020–2025. The temporal limitation ensures that findings reflect recent theoretical and methodological advancements, particularly the growing integration of HRV in mindfulness and emotion regulation research. The focus on this timeframe also aligns with the post-pandemic research surge exploring psychophysiological resilience mechanisms.

Inclusion and Exclusion Criteria

Inclusion Criteria

1. Articles are published in either English or Indonesian.
2. Publications within the period 2020–2025, in accordance with the latest developments in psychology, neurobiology, and mental health research.
3. Articles based on empirical research (quantitative, qualitative, or mixed methods) as well as conceptual studies addressing the relationship among mindfulness, HRV, and emotion regulation.
4. Articles published in reputable journals (Scopus Q1–Q4 or nationally accredited journals) and available in full-text format.

Exclusion Criteria

1. Articles in the form of editorials, commentaries, opinions, or short reviews without systematic analysis.
2. Academic works such as these, dissertations, or internal reports that are not officially published.
3. Articles discussing only mindfulness or HRV in isolation without linking them to emotion regulation.

4. Articles without an abstract, lacking full-text access, or not presenting transparent data/methodology.

By applying these criteria, the selected literature is expected to fully support the research objective, namely, to understand HRV as a neurobiological biomarker of the effects of mindfulness on emotion regulation.

Result and Discussion

Result

Mindfulness has been shown to play a crucial role in enhancing the flexibility of the autonomic nervous system, as evidenced by increased heart rate variability (HRV). HRV is considered an objective indicator of the balance between sympathetic and parasympathetic nervous system activity, thereby serving to explain the neurobiological mechanisms underlying individuals' ability to regulate emotions. Findings across the literature indicate that mindfulness practices whether through meditation or conscious breathing exercises can reduce physiological stress responses and increase parasympathetic activity, thereby strengthening adaptive emotion regulation.

Furthermore, HRV enables researchers and clinical practitioners to bridge the physiological and psychological aspects of emotion regulation. Mindfulness not only influences individuals' subjective experiences such as increased self-awareness and reduced emotional reactivity—but also provides measurable neurophysiological evidence. Thus, HRV serves as a relevant biomarker for evaluating the effectiveness of mindfulness interventions, both in general populations and in patients with psychological disorders such as anxiety, depression, and post-traumatic stress. Although existing findings consistently demonstrate the benefits of mindfulness on HRV, methodological challenges remain. Variations in HRV measurement instruments, the duration and intensity of mindfulness interventions, and sample heterogeneity all contribute to differences in research outcomes. Therefore, future studies should strengthen methodological standards and broaden population diversity to establish HRV as a valid and universal biomarker for understanding the neurobiological effects of mindfulness on emotion regulation.

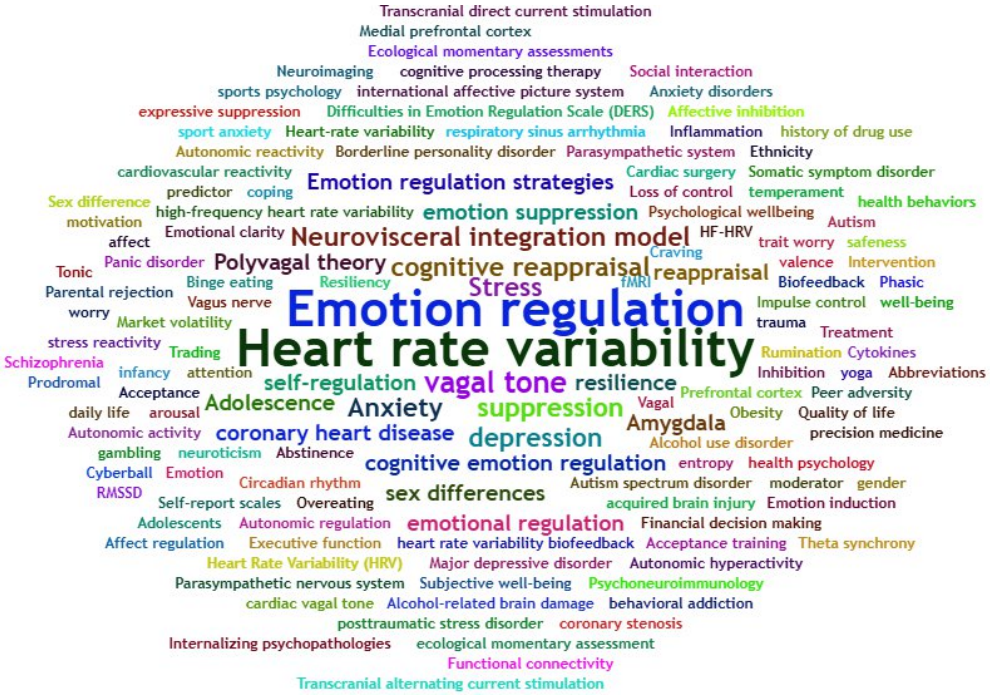

Figure 1 Most Frequently discussed topics (Word Frequency Cloud)

Based on Figure 1, the results of the Word Frequency Cloud analysis indicate that the most prominent topic in the literature is Heart Rate Variability (HRV), followed by other major themes, including Emotion Regulation, Anxiety, Depression, and the Neurovisceral Integration Model. The dominance of HRV as the primary keyword underscores its recognition as a crucial physiological indicator in understanding the mechanisms of emotion regulation and mental health. This finding aligns with various studies that identify HRV as a neurobiological biomarker capable of reflecting the balance of the autonomic nervous system in responding to stress and emotions (Goessl et al., 2017).

In addition to HRV, the topic of Emotion Regulation appears quite prominently, indicating that research on emotion regulation is closely linked with HRV. Emotion regulation, whether through cognitive strategies such as reappraisal or suppression, plays a crucial role in understanding individual psychological health. The connection between HRV and emotion regulation has been widely examined in the context of psychological disorders such as anxiety disorders, depression, and PTSD, showing that low HRV is often associated with difficulties in managing emotions adaptively.

Keywords such as Polyvagal Theory, Vagal Tone, and Autonomic Regulation reinforce the view that HRV is strongly related to the physiological functions of the parasympathetic nervous system through vagal activity. This underscores the relevance of polyvagal theory in explaining the relationship between physiological responses of the body and psychological processes such as stress reactivity, emotional suppression, and cognitive reappraisal. Thus,

HRV is not merely a cardiac indicator but also reflects the neurobiological interconnectedness between the brain, nerves, and emotions.

Moreover, keywords such as Mindfulness, Resilience, and Well-being emphasise that mindfulness-based interventions are increasingly being investigated in relation to HRV and emotion regulation. Mindfulness has been shown to enhance physiological flexibility through increased HRV, which in turn contributes to greater emotional resilience and improved mental health. In other words, this topic mapping suggests that current research trends integrate psychological approaches (such as mindfulness and emotion regulation) with biological indicators (HRV) to achieve a more comprehensive understanding of individual well-being.

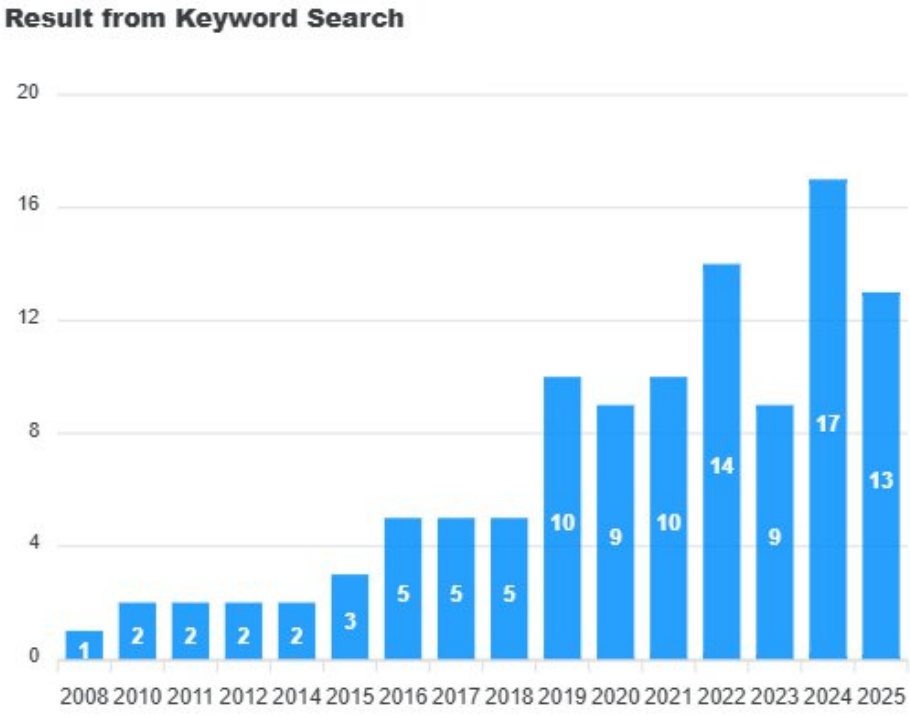

Figure 2 Research Delopment on Heart Rate Variability in Relation to Emotion Regulation, Neurobiological Biomarkers, and Mindfulness Effects on Emotion Regulation

Based on Figure 2, the development of research related to Heart Rate Variability (HRV) on Emotion Regulation, Neurobiological Biomarkers, and Mindfulness Effects on emotion regulation exhibits a dynamic trend throughout the period from 2008 to 2025. During the early period, from 2008 to 2014, the number of studies was relatively low and remained stable at around 1–2 publications per year. This suggests that research on HRV in relation to emotion regulation and mindfulness was still in its early exploratory stage and had not yet garnered significant academic attention.

Between 2015 and 2018, a more significant increase occurred, although still moderate, with a range of 3 to 5 publications per year. This growth reflects an increasing academic interest in HRV as a neurobiological biomarker, along with the advancement of studies on the relationship between the autonomic nervous system, emotion regulation, and mindfulness-based psychological interventions. During this period, HRV began to be viewed as having broader clinical and practical relevance in the fields of health psychology and neuroscience.

The research trend showed even stronger growth during the 2019-2022 period, with the number of publications reaching double digits, specifically 9 to 14 studies per year. This significant increase suggests that HRV has gained greater academic legitimacy as a crucial physiological indicator for understanding the mechanisms of emotion regulation. In this period as well, HRV was increasingly utilized in studies linking mindfulness interventions with mental health, including among populations with anxiety disorders, depression, and PTSD.

The peak number of studies was observed in 2024, with 17 publications, indicating that this topic has become increasingly mainstream within the scientific literature. Although the number of studies slightly declined in 2025 to 13, the overall trend demonstrates consistent and sustained growth. This highlights that HRV, as a neurobiological biomarker in the context of mindfulness and emotion regulation, is increasingly recognized and continues to be developed, both theoretically and clinically. Thus, future research directions are likely to focus more on integrating HRV with psychological approaches, digital interventions, and personalized therapies to improve individual mental well-being.

Based on the literature review summarised in the table, it is evident that Heart Rate Variability (HRV) plays a crucial role as a neurobiological biomarker in understanding the effects of mindfulness on emotion regulation. Several studies have focused on mindfulness interventions, either in the form of randomised controlled trials (RCTs) or online-based interventions, demonstrating that mindfulness can enhance emotion regulation skills by improving autonomic nervous system functioning as reflected in HRV (Wenxiao et al., 2025; Francesca et al., 2024; Aleksandra et al., 2022). This underscores that HRV not only represents the body's physiological condition but also reflects an individual's adaptive capacity in responding to stress, anxiety, and psychological distress. Thus, HRV can be used as an objective indicator for evaluating the effectiveness of mindfulness interventions in enhancing psychological well-being.

Studies involving children, adolescents, and adults have demonstrated that mindfulness is closely linked to the development of effective emotion regulation strategies and the enhancement of resilience capacity. For example, research on Chinese migrant children

(Wenxiao et al., 2025) demonstrated that a six-week mindfulness training program contributed to greater inner calm and reduced mind wandering. Among nursing students (Mikyoung et al., 2021), mindfulness was found to enhance achievement-related emotions through the mediation of emotion regulation. The consistency of these findings reinforces the argument that mindfulness can influence neurobiological mechanisms represented by HRV, thereby improving individuals' emotional responses across various population groups. This suggests that mindfulness is not only relevant for clinical populations but can also be applied in educational and developmental contexts for adolescents.

In addition, studies focusing on clinical conditions provide strong evidence regarding the relevance of HRV as a neurobiological biomarker. A study by Laura et al. (2025) on patients with somatic symptom disorder showed that HRV and autonomic reactivity were associated with individuals' ability to manage negative emotions such as sadness. Similarly, research (Debra et al., 2024) on children with autism found that HRV can be used to evaluate the outcomes of emotion regulation interventions. This highlights that HRV is capable of capturing neurobiological changes resulting from mindfulness-based emotion regulation training, making it a more objective measure compared to self-report alone. Thus, HRV serves as an important instrument in bridging the understanding between the physiological and psychological aspects of emotion regulation. Interestingly, several studies have highlighted HRV in the context of social interactions and everyday life dynamics. Research by Carlene et al. (2023) demonstrated that HRV varies according to emotional valence and the regulation strategies employed during social interactions.

In contrast, Gillian et al. (2024) emphasised that HRV and affective inhibition influence adolescents' emotion regulation in daily life. These findings expand our understanding of how mindfulness operates not only at the individual level but also shapes the quality of social relationships through enhanced emotion regulation, as reflected in HRV. In other words, HRV can be viewed as a bridge linking individual psychological health with social dynamics, reinforcing the notion that mindfulness has broad implications for social and interpersonal life.

In the context of minority populations, Ángel et al. (2020) demonstrated that mindfulness, emotion regulation, and social support can moderate the relationship between depressive symptoms and resilience in Hispanic young adults. This suggests that HRV, which is associated with the capacity for emotion regulation, may reflect how mindfulness contributes to psychological resilience in the face of social and psychological pressures. From a neurobiological perspective, mindfulness functions to strengthen the parasympathetic nervous system, thereby enhancing heart rate variability as an indicator of emotional

adaptability. Thus, mindfulness not only improves emotion regulation at the intrapersonal level but also supports psychological functioning within diverse community contexts.

Overall, this literature synthesis demonstrates that HRV can serve as a valid neurobiological biomarker for assessing the impact of mindfulness on emotion regulation across both clinical and non-clinical contexts. HRV enables researchers better to understand the physiological mechanisms underlying mindfulness-based psychological interventions, while also providing opportunities to integrate objective measures into mental health evaluations. By combining HRV measurement with psychological assessments, future research can offer a more comprehensive understanding of how mindfulness enhances emotion regulation and well-being. This not only contributes to theoretical development but also carries practical implications for the advancement of evidence-based interventions in clinical psychology, education, and public health.

Discussion

Mindfulness and HRV in Non-Clinical Populations

Mindfulness has been shown to enhance autonomic flexibility and parasympathetic dominance, as reflected by increases in high-frequency heart rate variability (HF-HRV) and root mean square of successive differences (RMSSD). These HRV parameters serve as objective indicators of the body's adaptive capacity to regulate stress and maintain emotional equilibrium. Studies consistently demonstrate that mindfulness-based practices—such as meditation, mindful breathing, and body scan techniques—reduce sympathetic overactivation while strengthening vagal tone, thereby improving emotion regulation and psychological resilience.

Empirical findings support the role of mindfulness in improving HRV and emotion regulation among general populations. For instance, Wenxiao et al. (2025) found that a six-week mindfulness training among Chinese migrant children increased HRV indices and reduced mind-wandering, resulting in greater emotional stability. Similarly, Mikyoung et al. (2021) reported that mindfulness practices among nursing students enhanced achievement-related emotions through improved emotion regulation, mediated by HRV changes. These outcomes indicate that mindfulness contributes to both subjective psychological balance and measurable neurophysiological regulation, confirming HRV's role as a neurobiological biomarker of emotional adaptability.

The relationship between HRV and mindfulness also supports the Polyvagal Theory (Porges, 2011), which posits that vagal activation promotes social engagement, calm states, and emotional safety. High HRV, as observed following mindfulness interventions, reflects an

integrated response between physiological regulation and cognitive-emotional control. These findings align with the Neurovisceral Integration Model (Thayer & Lane, 2009), which emphasizes the dynamic interaction between prefrontal cortical networks and autonomic function in maintaining emotional stability. Thus, mindfulness appears to optimize neurovisceral integration, fostering adaptive emotion regulation both physiologically and psychologically.

HRV as a Clinical Biomarker

Evidence from clinical populations further reinforces HRV's role as a neurobiological biomarker in understanding the effects of mindfulness on emotion regulation. A study by Laura et al. (2025) on patients with somatic symptom disorder found that HRV levels were positively associated with the ability to regulate negative affect, including sadness and frustration. Likewise, Debra et al. (2024) demonstrated that HRV served as a reliable indicator of treatment progress in children with autism spectrum disorder, where improvements in HRV paralleled better emotional control and reduced behavioral dysregulation.

These results suggest that HRV not only captures autonomic changes resulting from mindfulness-based interventions but also provides an objective physiological complement to self-reported emotional outcomes. The advantage of using HRV lies in its ability to measure the underlying autonomic processes that mediate emotion regulation, offering a bridge between subjective emotional experience and quantifiable biological mechanisms. Moreover, clinical applications of HRV extend to psychological disorders such as anxiety, depression, and post-traumatic stress disorder (PTSD), where low HRV is commonly associated with maladaptive emotional responses and chronic stress activation.

Gillian et al. (2024) emphasized that HRV patterns during adolescence are closely linked to affective inhibition and emotional control in daily life, while Carlene et al. (2023) highlighted how HRV fluctuates according to emotional valence and social interaction quality. These findings illustrate that mindfulness interventions not only influence individual emotional regulation but also extend to social and interpersonal functioning by stabilizing autonomic reactivity. This highlights HRV's potential as a tool for monitoring mindfulness-based clinical therapies, enabling clinicians to track autonomic recovery and emotional resilience over time.

Methodological Heterogeneity and Thematic Trends

While the reviewed studies consistently demonstrate positive associations between mindfulness and HRV, several methodological limitations hinder the comparability of findings. Variations in HRV recording duration (short-term vs. long-term), data processing (time-domain vs. frequency-domain analyses), and intervention formats (in-person, online,

or hybrid mindfulness training) contribute to inconsistencies in results. Sample heterogeneity across studies ranging from adolescents to elderly adults and clinical versus healthy participants further complicates cross-study synthesis.

The Word Frequency Cloud (Figure 1) highlights "Heart Rate Variability (HRV)" as the most prominent keyword, followed by "Emotion Regulation," "Mindfulness," "Anxiety," and "Depression." This pattern underscores HRV's growing recognition as a physiological indicator of emotional and mental health mechanisms. Related concepts such as Polyvagal Theory, Vagal Tone, and Autonomic Regulation reinforce the neurophysiological basis of HRV, connecting it to the parasympathetic pathways underlying emotional resilience. Moreover, frequent references to "Resilience" and "Well-being" reveal a conceptual shift from merely reducing psychological distress to promoting adaptive recovery and flourishing through mindfulness-based approaches.

Figure 2 illustrates the trajectory of HRV-related research from 2008 to 2025, showing an exponential increase in publications, peaking in 2024. This surge reflects the field's growing interest in HRV as a biomarker integrating psychological interventions with neurophysiological evidence. Notably, the inclusion of randomized controlled trials (RCTs) and longitudinal designs after 2019 has improved the robustness of causal inferences regarding mindfulness and emotion regulation.

Despite these advances, future research should prioritize standardized HRV measurement protocols (e.g., five-minute resting baseline, consistent sampling rates) and employ multi-modal designs that integrate HRV with neuroimaging or hormonal biomarkers. Methodological transparency, particularly in data cleaning and artifact correction, remains essential for replicability. Additionally, cultural and linguistic factors influencing mindfulness practice should be addressed, as they may affect both psychological engagement and autonomic responsiveness.

Practical and Theoretical Implications

From a practical perspective, HRV measurement provides a valuable biofeedback tool in mindfulness-based interventions, allowing individuals to monitor physiological regulation in real-time. Clinically, integrating HRV metrics with therapeutic programs (e.g., Mindfulness-Based Stress Reduction or Mindfulness-Based Cognitive Therapy) may enhance treatment personalization and facilitate early detection of stress dysregulation. Educational settings can also benefit from HRV-informed mindfulness training to improve students' emotional balance, focus, and resilience.

Theoretically, these findings strengthen the neurobiological understanding of how mindfulness supports emotion regulation through top-down cortical control and bottom-up

autonomic modulation. HRV serves as a quantifiable marker of this integration, aligning with both Polyvagal and Neurovisceral Integration frameworks. Thus, HRV transcends its traditional role as a cardiac metric, emerging as a multidimensional index that reflects psychophysiological coherence and adaptive self-regulation.

Conclusions

This systematic review synthesizes evidence from 2020–2025 on the relationship between mindfulness, emotion regulation, and Heart Rate Variability (HRV) as a neurobiological biomarker. Across diverse empirical designs including randomized controlled trials (RCTs), school-based programs, and online mindfulness interventions findings consistently demonstrate that mindfulness practices enhance HRV parameters such as RMSSD and HF power, which are associated with improved emotional stability and self-regulatory capacity. These outcomes provide convergent support for the polyvagal theory and the neurovisceral integration model, underscoring HRV's role as a physiological marker of adaptive emotion regulation.

Practically, HRV monitoring offers valuable applications for real-time evaluation of mindfulness-based interventions in clinical, educational, and workplace contexts. Integration with wearable technologies enables continuous biofeedback, facilitating early detection of emotional dysregulation and promoting preventive mental health care. However, the synthesis also identifies methodological challenges, including inconsistent HRV recording protocols, variability in intervention duration and intensity, and limited standardization across studies, which constrain cross-study comparability and generalization. This systematic review contributes to the field by providing the most recent synthesis of HRV as a neurobiological indicator of mindfulness-based emotion regulation between 2020 and 2025, highlighting key methodological gaps and translational potential. Future research should emphasize longitudinal, multimodal designs combining HRV, neuroimaging, and behavioral data, and develop personalized intervention frameworks aligned with individuals' physiological and emotional profiles. Such an approach will advance the precision and applicability of HRV as a biomarker for evaluating mindfulness-based mental health interventions.

References

Aleksandra, Isham, A., Palacio-Gonzalez, & Barbara, D. (2022). *The Effects of an Online Mindfulness Intervention on Emotion Regulation upon Autobiographical Memory Retrieval in Depression Remission*.

Álvarez-Pérez, Y., Rivero-Santana, A., Perestelo-Pérez, L., Duarte-Díaz, A., Ramos-García, V., Toledo-Chávarri, A., Torres-Castaño, A., León-Salas, B., Infante-Ventura, D.,

González-Hernández, N., Rodríguez-Rodríguez, L., & Serrano-Aguilar, P. (2022). Effectiveness of Mantra-Based Meditation on Mental Health: A Systematic Review and Meta-Analysis. *International Journal of Environmental Research and Public Health*, *19*(6), 3380. https://doi.org/10.3390/ijerph19063380

Ángel, M., Cano, F. G., Castro, M., Rosa, Hortensia, A., A., W., Vega, M., Sánchez, P., Rojas, D., Ramírez-Ortiz, T., Taskin, G., Prado, S. J., Schwartz, D., Córdova, C. P., & Salas-Wri. (2020). *Depressive Symptoms and Resilience among Hispanic Emerging Adults: Examining the Moderating Effects of Mindfulness, Distress Tolerance, Emotion Regulation, Family Cohesion, and Social Support, Behavioral Medicine*.

Appelhans, B. M., & Luecken, L. J. (2006). Heart rate variability as an index of regulated emotional responding. *Review of General Psychology*, *10*(3), 229–240.

Bigler, E. D. (2016). Systems Biology, Neuroimaging, Neuropsychology, Neuroconnectivity and Traumatic Brain Injury. *Frontiers in Systems Neuroscience*, *10*. https://doi.org/10.3389/fnsys.2016.00055

Breedvelt, J. J. F., Amanvermez, Y., Harrer, M., Karyotaki, E., Gilbody, S., Bockting, C. L. H., Cuijpers, P., & Ebert, D. D. (2019). The Effects of Meditation, Yoga, and Mindfulness on Depression, Anxiety, and Stress in Tertiary Education Students: A Meta-Analysis. *Frontiers in Psychiatry*, *10*. https://doi.org/10.3389/fpsyt.2019.00193

Carlene, D.-L., W., T., Smith, P. G., Williams, B. N., & Uchino. (2023). Heart rate variability during social interaction: Effects of valence and emotion regulation. *International Journal of Psychophysiology*.

Casey, B. J., Getz, S., & Galvan, A. (2008). The adolescent brain. *Developmental Review*, *28*(1), 62–77. https://doi.org/10.1016/j.dr.2007.08.003

Craven, M. R., Quinton, S., & Taft, T. H. (2019). Inflammatory bowel disease patient experiences with psychotherapy in the community. *Journal of Clinical Psychology in Medical Settings*, *26*(2), 183–193.

de Moura Targino, R., Esmeraldo, M. A. A., Cajazeiras Falcão, I., & Macêdo Melo, K. (2025). Intersection of Brain Complexity, Functional Connectivity, and Neuropsychology: A Systematic Review. *Cureus*. https://doi.org/10.7759/cureus.80719

Debra, Reisinger, M. S., Goodwin, P. S., Horn, L. M., Schmitt, M. C., Coffman, R. C., & Shaffer. (2024). Examining the feasibility and utility of heart rate variability on intervention outcomes targeting emotion regulation in autism: a brief report. *Scientific Reports*.

El Morr, C., Ritvo, P., Ahmad, F., Moineddin, R., & M. T. (2020). Effectiveness of an 8-Week Web-Based Mindfulness Virtual Community Intervention for University Students on Symptoms of Stress, Anxiety, and Depression: Randomized Controlled Trial. *Journal of Medical Internet Research*, *22*(9).

Francesca, S., Mattea, R., Quinto, S., Ghiroldi, N. F., Montecucco, F., Presaghi, L., Iani, F., &

Vincenzo. (2024). *The mediation role of emotion regulation strategies on the relationship between mindfulness effects, psychological well-being and distress among youths*.

Gillian, D., Nathalie, M., & Matteo, G. (2024). Cognitive control processes and emotion regulation in adolescence: Examining the impact of affective inhibition and heart-rate-variability on emotion regulation dynamics in daily life. *Developmental Cognitive Neuroscience*.

Gkintoni, E., Skokou, M., & Gourzis, P. (2024). Integrating Clinical Neuropsychology and Psychotic Spectrum Disorders: A Systematic Analysis of Cognitive Dynamics, Interventions, and Underlying Mechanisms. *Medicina*, *60*(4), 645. https://doi.org/10.3390/medicina60040645

Goessl, V. C., Curtiss, J. E., & Hofmann, S. G. (2017). The effect of heart rate variability biofeedback training on stress and anxiety: a meta-analysis. *Psychological Medicine*, *47*(15), 2578–2586. https://doi.org/10.1017/S0033291717001003

Karsh, B.-T., Holden, R. J., Alper, S. J., & Or, C. K. L. (2006). A human factors engineering paradigm for patient safety: designing to support the performance of the healthcare professional: Figure 1. *Quality in Health Care*, *15*(suppl 1), i59–i65. https://doi.org/10.1136/qshc.2005.015974

Laura, K., Johannes, S., & Alexandra, M. (2025). Heart Rate Variability, Autonomic Reactivity, and Emotion Regulation during Sadness Induction in Somatic Symptom Disorder. *International Journal of Behavioral Medicine*.

Mikyoung, L., Seong, K., & Jang. (2021). *Mediating effects of emotion regulation between socio-cognitive mindfulness and achievement emotions in nursing students, Healthcare (Switzerland*.

Ong, J. C., Manber, R., Segal, Z., Xia, Y., Shapiro, S., & Wyatt, J. K. (2014). A Randomized Controlled Trial of Mindfulness Meditation for Chronic Insomnia. *Sleep*, *37*(9), 1553–1563. https://doi.org/10.5665/sleep.4010

Pascoe, M. C., Thompson, D. R., & Ski, C. F. (2017). Yoga, mindfulness-based stress reduction and stress-related physiological measures: A meta-analysis. *Psychoneuroendocrinology*, *86*, 152–168.

Smith, R., Thayer, J. F., Khalsa, S. S., & Lane, R. D. (2017). The hierarchical basis ofneurovisceral integration. *Neuroscience and Biobehavioral Reviews*, *75*. https://doi.org/10.1016/j.neubiorev.2017.02.003

Virgili, M. (2015). Mindfulness-Based Interventions Reduce Psychological Distress in Working Adults: a Meta-Analysis of Intervention Studies. *Mindfulness*, *6*(2), 326–337. https://doi.org/10.1007/s12671-013-0264-0

Wenxiao, G., Tao, L., Yanyan, D., Sisi, W., Zhenzhen, Q., & Yuzheng, W. (2025). *The Effects of*

Six-Week Mindfulness Training on Mindfulness, Inner Peace, Emotion Regulation, and Mind Wandering in Chinese Migrant Children: A.

Zaccaro, A., Piarulli, A., Laurino, M., Garbella, E., Menicucci, D., Neri, B., & Gemignani, A. (2018). How breath-control can change your life: a systematic review on psycho-physiological correlates of slow breathing. *Frontiers in Human Neuroscience*, *12*, 409421.