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Virtual forests and human well-being: A systematic review of forest characteristics and psycho-physiological responses

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A R T I C L E I N F O

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A B S T R A C T

Virtual reality (VR) is emerging as a tool to study the well-being benefits of forest exposure under controlled conditions, with potential implications for forest planning and policy design. This paper systematically reviews 34 VR-based studies to assess how forest features are represented and how their effects on human well-being are measured. The analysis reveals significant inconsistencies between VR-based evidence and established knowledge from real forest settings. Most studies rely on simplified forest representations, with limited attention to key structural attributes such as density, understory, and deadwood, despite their relevance for recreational preferences and ecosystem services. Additionally, mixed and coniferous forests—often preferred in real contexts—are underrepresented. Multisensory components remain only partially integrated, with sound widely used but other sensory inputs largely neglected. From a policy perspective, these limitations reduce the transferability of VR findings to real-world forest management. At the same time, VR offers advantages in terms of experimental control and the ability to isolate specific forest features, supporting causal inference. The review also highlights a mismatch between indicators used in VR and those adopted in field studies, which complicates comparison and policy interpretation. Overall, VR represents a promising but still underdeveloped tool for informing forest policy aimed at enhancing human well-being. Future research should prioritize more realistic and standardized forest representations, improved multisensory integration, and closer alignment with policy-relevant indicators to strengthen the applicability of VR-based evidence.

1. Introduction

The relationship between forest exposure and individual physiological and psychological responses is increasingly being investigated through virtual reality (VR) (Browning et al., 2020). Real forest environments are complex, variable, and difficult to manipulate experimentally. As a result, it remains challenging to isolate how specific forest characteristics shape perceived restoration, psychological well-being, physiological responses, and, ultimately, the policy-relevant value of forest experiences. Scientific interest in VR is growing, both as a potential substitute for and as a complement to real forest experiences. Accordingly, several studies have directly compared VR-based simulations with real natural settings (Browning et al., 2020; Mattila et al., 2020) while others have examined differences between immersive VR and traditional 2D photos or videos (Mokas et al., 2021; Liszio et al., 2018). Unlike 2D media, VR enables full immersion in computer-generated environments, providing a more realistic and engaging experience (Bohil et al., 2011; Waterworth et al., 2015).

This paper asks whether virtual reality can provide a credible and policy-relevant method for studying the well-being benefits of forest exposure. To answer this question, the work systematically reviews studies that examine the association between forest characteristics represented in VR settings and individual well-being. The review has three related aims. First, it identifies which forest characteristics have been represented in immersive VR studies and how they have been linked to physiological and psychological responses. Second, it highlights research gaps and methodological good practices for future VR-based forest research. Third, it discusses the implications of these findings for the use of immersive technologies in public policies aimed at promoting well-being.

The review is positioned within a growing forest policy and economics literature that examines how people perceive, use, and value forests beyond timber production. Recent studies have analysed the economic value of forest and green-space visits (Phelan et al., 2025), seasonal variation in recreational forest values (de Kruiff et al., 2025), willingness to pay for old-growth forest conservation

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(Getzner et al., 2025), public preferences for different forest landscape configurations (Derks et al., 2026), and visual landscape effects in spatial forest planning (Heinonen et al., 2026). VR-based research might complement these studies with the investigation of psychological and physiological responses of forest exposure in an experimentally-controlled environment. From a physiological perspective, exposure to forest environments promotes relaxation, reduces salivary cortisol levels, activates the parasympathetic nervous system, and inhibits sympathetic activity (Olafsdottir et al., 2020; Lee et al., 2012; Park et al., 2010; Bach et al., 2021). Additional positive outcomes include lower blood pressure, reduced heart rate, and enhanced immune functioning, such as increased activity of natural killer cells (Lee et al., 2012; Park et al., 2010).

Evidence of the mental health benefits of forest exposure is equally strong. Spending time in forest environments has been shown to reduce negative emotions, enhance positive affect, improve perceived restoration, elevate mood, lower perceived stress, and increase feelings of vitality (Tyrväinen et al., 2014; Olafsdottir et al., 2020; Bielinis et al., 2020; Martens et al., 2011; Phelan et al., 2025). At the same time, immersive practices in forest environments—such as forest bathing, nature meditation, and forest therapy—have grown in popularity (Liu et al., 2025; Paletto et al., 2024a), demonstrating documented benefits for individual well-being (Chen et al., 2025; Mazzoleni et al., 2024; Muro et al., 2022; Peterfalvi et al., 2021).

Although a substantial body of evidence has been accumulated, the wide diversity of forest types, structural characteristics, and measured physiological and psychological responses still calls for further investigation. Recent studies have started to examine how specific forest features, seasonal variations, and the types of activities carried out in forests influence well-being (Peterfalvi et al., 2021; Mazzoleni et al., 2024; Clark et al., 2023; Bielinis et al., 2021). However, knowledge about the distinct benefits associated with particular forest characteristics remains limited.

At the same time, field-based research presents important methodological challenges. Conducting experiments in real forest environments is costly and difficult to control. Each visit is influenced by external conditions beyond the researchers' control, such as weather, wind intensity, or unexpected events (e.g., wildlife encounters). These factors may introduce variability that complicates the interpretation of results.

Laboratory-based approaches can therefore play a crucial role, particularly in designing interventions for individuals who cannot easily access real forests due to time constraints, geographical distance, or psychophysical limitations. In this context, VR offers a relatively inexpensive and flexible solution to recreate forest environments in controlled settings, where experimental stimuli can be systematically manipulated. However, the advantages of stimulus control in VR are partly offset by reduced realism and the absence of physical contact with the natural environment.

Without a clear understanding of the specific effects of VR-based forest exposure, there is a risk of developing interventions that are ineffective or poorly targeted. For this reason, the aim of this review is to critically assess the strengths and limitations of VR applications in forest research, in order to clarify their potential, identify best practices, and propose methodological guidelines. The ultimate goal is to provide guidance on how to correctly represent forest characteristics to make VR a reliable tool for forest policy and economics research.

In light of these considerations, the following research questions guide this study: 1) *How have forest environments been recreated and studied in laboratory settings using VR, and which specific characteristics have been considered?* 2) *Which psychophysical and psychological measures have been employed to assess the effects of VR-based forests on individual well-being?* and 3) *Which combinations of forest characteristics and psychophysical indicators remain underexplored, and what do these gaps imply for future VR research and for the policy use of immersive technologies to promote well-being?*

This review provides a comprehensive overview of the current scientific literature on the use of virtual reality in forest research. The study follows the PRISMA framework (Page et al., 2021) to ensure a transparent and systematic process of article selection and data extraction. In addition, a bibliometric network analysis conducted with VOSviewer is used to map thematic connections within the field and to examine patterns of international collaboration.

From a methodological perspective, the review classifies the characteristics of virtual forest environments represented in the selected studies and systematically links them to the psychophysiological and psychological indicators used to assess well-being outcomes.

The remainder of the manuscript is structured as follows. Section 2 outlines the methodological approach, including the application of the PRISMA framework. Section 3 presents the results of the review. Section 4 discusses the main findings and advances methodological recommendations. Finally, Section 5 concludes the paper.

2. Materials and methods

2.1. Search strategy

This review was conducted following the PRISMA (Page et al., 2021) guidelines for systematic reviews. The literature search (i.e., identification phase) was performed using the Scopus database using the following keywords: "forest" (to identify studies related to forest settings); "virtual reality" (to capture VR usage); and "headset", "head-mounted", "helmet", "glasses", "goggles", or "immersive" (to restrict the analysis to immersive VR). Terms such as "machine learning", "random forest", and "decision tree" were explicitly excluded to prevent retrieving algorithmic or datamining studies.[1]

2.2. Inclusion and exclusion criteria

Studies were selected based on the following inclusion criteria:

1. Use of immersive virtual reality;
2. Presence of at least one forest setting;
3. Use of psychophysical measurements to isolate the effects of forest scenarios from other experimental conditions;
4. Provision of a minimal description and/or visual representation of the forest scenario (e.g., photographs, location details, or video links).

The following exclusion criteria were applied:

1. Reviews, book chapters, and conference reviews;
2. Non-English publications;
3. Lack of immersive virtual reality usage;
4. Absence of forest settings;
5. Lack of psychological or physiological measurements;
6. Absence of distinct measurements for each tested scenario;
7. Lack of visual or textual descriptions of the scenarios.

2.3. Screening and data extraction

The initial body of literature was reduced by excluding irrelevant publications, such as review articles, non-English publications, and book chapters. Fig. 1 details the number of articles excluded at each stage of the screening process. A full-text assessment of the remaining articles was then conducted to eliminate studies failing to meet the predefined inclusion criteria. To ensure completeness, a secondary check was

[1] The final query used was: *(TITLE-ABS-KEY (forest*) AND TITLE-ABS-KEY (virtual AND reality) AND TITLEABS-KEY (headset OR head-mounted OR helmet OR glasses OR goggles OR immersive) AND NOT TITLE-ABS-KEY ("machine learning" OR "random forest" OR "decision tree*"))*

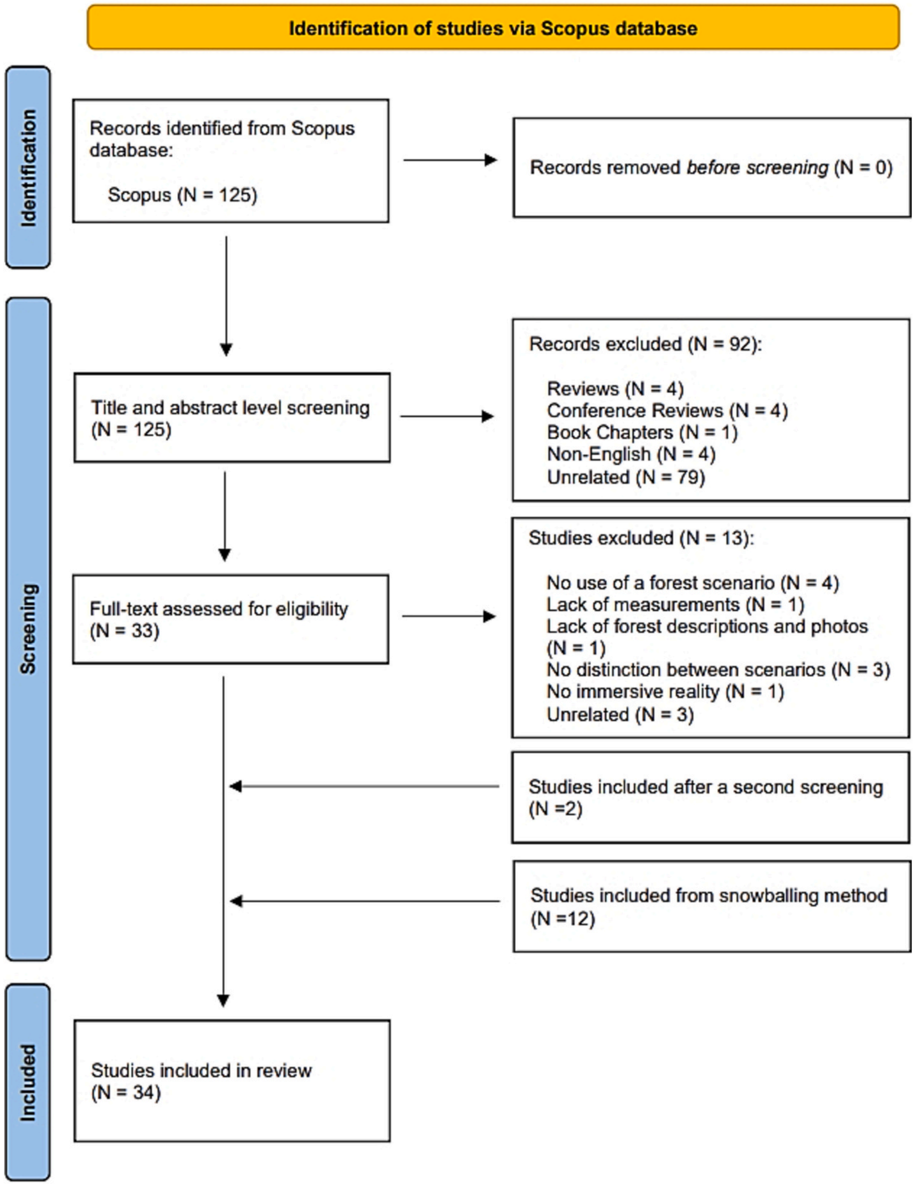

Fig. 1. PRISMA flow diagram

performed on the initially excluded articles by searching their full texts for key terms such as *forest*, *virtual reality*, and related synonyms. Finally, additional relevant articles were identified through snowball sampling.

Extracted data included:

1. General information: author, title, year, source, and country of origin;
2. Forest setting characteristics: forest type, non-visual stimuli (olfactory/haptic/auditory), specific attributes (e.g., unmanaged, urban, dense, open, or secondary forest), permeability, canopy density, average tree height and diameter, presence of water, and understory stratification (including height and cover);
3. Psychological measures: scales or questionnaires employed;
4. Physiological measures;
5. Additional details: study aims, scenario comparisons, and experimental design.

Data on forest scenarios were extracted (1) directly from the text if descriptions were available; (2) from supplementary sources when locations were specified; and (3) via visual interpretation of images when textual descriptions and locations were insufficient. The extracted data were compiled in Excel, and bibliometric information was processed using VOSviewer (van Eck and Waltman, 2010) to visualize international collaborations and keyword co-occurrences.

3. Results

3.1. Included articles

An initial set of 125 studies was retrieved from the Scopus database. Many of these studies were not useful for the study and were excluded after abstract screening. In particular, 79 articles were excluded because they did not clearly investigate health outcomes due to VR forest exposure but used VR for other purposes. After the initial screening phase, 33 articles were selected for fulltext assessment. Of these, 13 were subsequently excluded for not meeting the predefined inclusion criteria (see Section 2.2). A secondary check led to the inclusion of two additional articles. Subsequently, a snowballing procedure—based on screening the reference lists of the selected studies—identified 12 further relevant papers that had not emerged in the initial Scopus search.

Ultimately, 34 articles were included in the final review (see Table A.1 in Appendix A).

3.2. Articles overview

The selected literature consists of 26 journal articles and 8 conference papers published between 2015 and 2024. The majority of studies employing VR forest scenarios were published between 2020 and 2023, with a slight decline in output observed in 2021.

Fig. 2 visualizes the VOSviewer map of international collaborations. This bibliometric network analysis is used as a complementary descriptive tool to contextualize the reviewed literature. The size of each node reflects the number of publications produced by the corresponding country. The links (L) between nodes indicate co-authorships, with thicker links representing stronger collaborations. Total Link Strength (TLS) denotes a country's overall collaborative network strength and is measured as the sum of the link strengths connecting that country with other countries in the coauthorship network. The clustering algorithm groups countries with dense mutual collaborations into color-coded clusters.

As shown in Fig. 2 and Table B.2 (see Appendix B), publications are widely distributed globally, featuring a central core led by China (9 publications), the USA (8), and Taiwan (5). Their centrality is confirmed by their collaboration metrics: the USA ranks first (L = 5, TLS = 6), followed by

Taiwan (L = 3, TLS = 5) and China (L = 2, TLS = 3). Countries such as Canada, Finland, Germany, Brazil, Sweden, France, Singapore, and Hong Kong also show consistent research activity and international collaboration, although at a comparatively lower level.

Fig. 3 presents the VOSviewer map of author and index keywords. Author keywords are terms selected directly by the authors of each article. Index keywords are standardized descriptors assigned to an article by professional indexers or automated classification systems within the database, Scopus in this case. Index Keywords in primary studies are assessed in terms of Occurrences (O), i.e. the count of the same keyword that occurs across contributions. Prior to generating the map, terms were harmonized using a custom thesaurus file. Applying a minimum threshold of three occurrences, 32 relevant keywords were identified.

The keyword '*virtual reality*' exhibited the highest metrics ([O] = 29, L = 31, TLS = 135). Other dominant keywords included '*humans*' (O = 11, L = 23, TLS = 81), '*female*' and '*male*' (both O = 7, L = 22, TLS = 67). Additional notable terms included '*forestry*' (O = 10), '*forests*' (O = 8), and '*physiology*' (O = 6).

3.3. Keywords

- clustered into three main themes:
- Cluster 1 (Red): Methodological and experimental aspects in virtual/real environments (e.g., '*humans*', '*forests*').
- Cluster 2 (Green): Experiential applications and well-being outcomes (e.g., '*stress*', '*virtual reality*', '*forestry*').

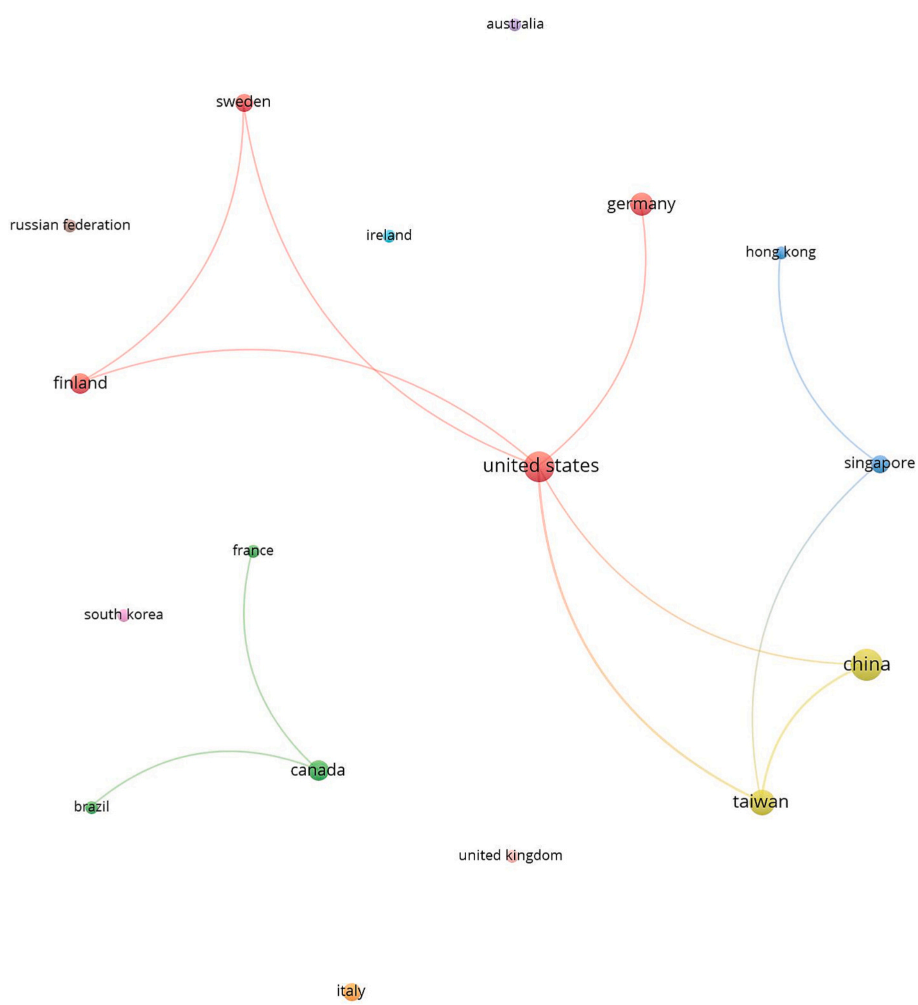

Fig. 2. VOSviewer map of co-authorship by country.

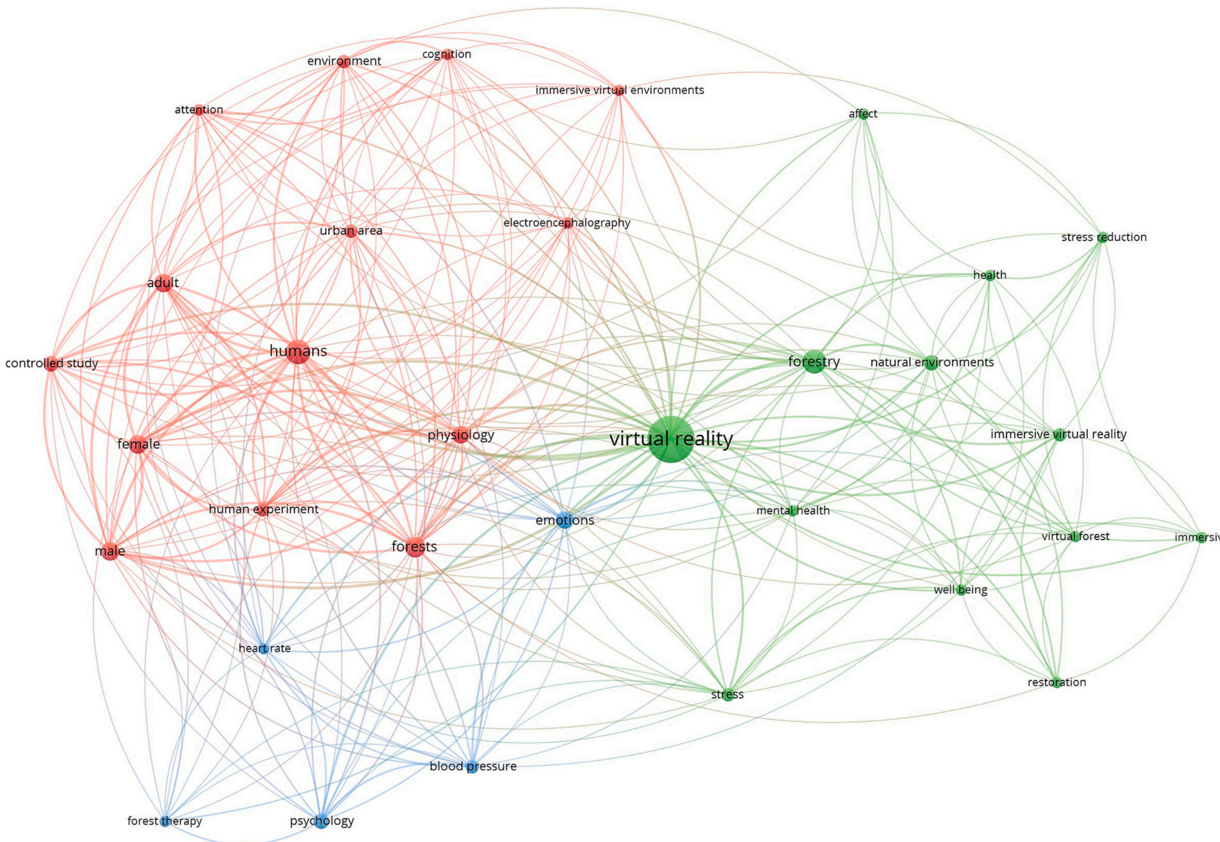

Fig. 3. VOSviewer map of keyword co-occurrence.

- Cluster 3 (Blue): Psychophysical indicators and therapeutic concepts (e.g., '*emotions*', '*blood pressure*', '*heart rate*', '*forest therapy*').

Two primary research trends emerged from the analysis. The first focuses broadly on investigating the psychophysical effects of natural environments through the use of VR (Browning et al., 2020; Chan et al., 2023; Davidov et al., 2022; Frigione et al., 2022; Hedblom et al., 2019). The second trend concentrates more specifically on the role of distinct forest characteristics and their influence on individual responses. (Hong et al., 2019; Hsieh and Li, 2022; Li et al., 2023, 2020; Masters et al., 2022). Some studies have focused specifically on forest therapy applications. These include the development of biofeedback systems for chronic pain management (Gromala et al., 2015), the stimulation of relaxation responses (Zhang et al., 2023b), the assessment of gait in individuals with multiple sclerosis(Riem et al., 2021, 2022), the evaluation of awe experiences (Chirico et al., 2018), and the investigation of multisensory integration processes(Lopes et al., 2022; Qi et al., 2022; Moosavi et al., 2024).

Experimental designs varied significantly across studies. Sixteen articles adopted within-subject designs, fourteen used between-subject designs, two employed mixed factorial designs, and three applied single-group formats. In most cases, VR forest environments were compared with real forests, urban settings, indoor environments, or other types of natural landscapes lacking tree cover or woody biomass.

3.4. Virtual scenarios and indicators

Table C.4 (see Appendix C) summarizes the forest characteristics and psychophysical indicators identified in the selected studies. These variables frequently co-occurred and should therefore not be viewed as mutually exclusive.

3.4.1. Virtual forest characteristics identified

Broadleaf forests were the most frequently represented forest type in VR settings (15 articles), followed by mixed forests (9 articles) and coniferous forests (6 articles). Auditory *stimuli* were frequently integrated into the virtual environments, while olfactory *stimuli* were included in only three studies and haptic feedback in just one. Certain structural forest attributes—such as understory height, canopy density, and tree diameter—were explicitly manipulated in only two studies (Li et al., 2023; Guo et al., 2024).Although not always formally described as experimental variables, understory vegetation (17 articles) and shrub layers (22 articles) were often visibly present in the virtual scenarios. Water elements were incorporated in 12 studies, while deadwood was represented in eight.

3.4.2. Physiological and psychological indicators identified

The descriptive statistics of country and number of studies that used physiological and psychological indicators are available in Appendix B. With respect to physiological measures, a total of 17 distinct measures were identified across the selected studies. Heart rate, heart rate variability, and electrodermal activity were the most commonly assessed indicators. In contrast, metrics such as blood pressure, electroencephalography (EEG), respiratory rate, and salivary amylase were investigated less frequently. The distribution of physiological indicators appears to reflect practical considerations, particularly the relative ease and feasibility of data collection.

Regarding psychological measures, 42 different indicators were identified. These indicators primarily assess restoration, stress, anxiety, and vitality. Psychological restoration emerged as the most extensively investigated construct, most commonly assessed with the Perceived Restorativeness Scale (PRS) and the Restoration Outcome Scale (ROS). Stress was frequently measured using the Perceived Stress Scale (PSS). In addition, multidimensional affect instruments—such as the PANAS-20, various versions of the Profile of Mood States (POMS), and measures based on the Circumplex Model of Emotion—were widely employed across studies.

3.4.3. Virtual forest characteristics and psycho-physical indicators

The list of papers that explored forest characteristics and the frequency of use of each characteristic is available in Appendix C. A recurring feature of the reviewed literature is the systematic association between specific virtual forest characteristics and selected physiological and psychological responses. This body of evidence can be organized around four analytical domains: forest type, environmental elements, structural attributes, and non-visual stimuli. From a policy and management perspective, these findings are relevant insofar as they clarify which forest configurations are most consistently linked to measurable indicators of human well-being. Broadleaf forests represent the most frequently examined virtual environments. Empirical assessment predominantly relies on autonomic indicators—particularly heart rate (HR), heart rate variability (HRV), electrodermal activity (EDA), and blood pressure (BP), while neurophysiological and biochemical markers, such as pupil diameter, respiratory rate, salivary amylase, skin temperature, blood volume pulse, and brain activity (EEG) are used less consistently. Notably, indicators related to cognitive fatigue, such as prefrontal oxygenation, are absent in this category. Psychological outcomes are mainly captured through multidimensional affect scales (e.g., PANAS, POMS, Affective Quality of Place measures, and Circumplex Model of Emotion), suggesting an emphasis on generalized emotional states rather than specific well-being dimensions. In coniferous forests, physiological assessment primarily focuses on central nervous system activity, as reflected in the frequent use of EEG, alongside peripheral autonomic measures such as pupil diameter, electrodermal activity, and skin temperature. Psychological outcomes include both single dimensions—such as anxiety (STAI-S-20), psychological restoration (PRS-16, ROS), and vitality (SVS-6)—and multidimensional tools, including PANAS-20, ZIPERS, Subject's Emotional State, and Semantic Differential (SD) scales. Mixed forests display the broadest physiological profiling, combining autonomic (HR, HRV, EDA) and neurophysiological (EEG) indicators, with occasional inclusion of measures of prefrontal oxygenation, salivary amylase, blood pressure, and pain. Psychological assessment remains largely reliant on multidimensional instruments (e.g., PANAS-20, STADI-S-20, POMS-37, POMS-30, BPOMS-30, SD) as well as on measures specifically designed to assess affective responses during physical activity, including the Feeling Scale (FS) and the Physical Activity Enjoyment Scale (PACES). Specific constructs, such as anxiety, relaxation, restoration, mindfulness, frustration, and vitality, are comparatively underexplored. Single-item measures are rarely used, except for stress and happiness. Additional typologies are investigated more selectively. Within virtual reality research, open forest environments are physiologically examined mainly through heart rate and heart rate variability, with occasional inclusion of blood pressure. Psychological outcomes are typically evaluated using the POMS-37 and the RCS, with particular attention to emotional states and perceived restoration. Studies conducted in dense forest virtual environments predominantly rely on physiological measures, including blood pressure, heart rate, heart rate variability, pupil diameter, electrodermal activity, and EEG. In contrast, psychological assessment is mainly based on multidimensional instruments (e.g., PANAS-10, PANAS-20, POMS-37), while psychological restoration—assessed through scales such as ROS, PRS-11, and RCS—represents the only dimension examined independently. In open forests virtual environments, physiological responses focus primarily on heart rate and heart rate variability, sometimes including blood pressure. Psychological outcomes are assessed using the POMS-37 and RCS, focusing on emotional state and perceived restoration. To investigate the physiological and psychological effects of secondary forests in virtual reality, studies typically employ a combination of autonomic measures—such as heart rate and heart rate variability—and central nervous system activity indexed by EEG, while emotional responses are conceptualized dimensionally using the Pleasure–Arousal–Dominance (PAD) model. Exposure to unmanaged forest environments in virtual reality is primarily examined through physiological stress markers—such as changes in blood pressure, electrodermal activity, and pupil diameter—whereas psychological responses show limited differentiation and are assessed exclusively using the PANAS-10 and ROS scales. The physiological effects of virtual urban forest environments are predominantly examined through electrodermal activity and EEG-derived indices of brain activity, while blood volume pulse and skin temperature are assessed less frequently. From a psychological perspective, restoration emerges as the most extensively investigated outcome, typically measured using the ROS, PRS-11, and PRS-16 scales. Research also addresses stress (SSS, PSS-14) and anxiety (STAI-S-20, STAI-S-6), in addition to vitality and broader affective states evaluated through multidimensional instruments such as the PANAS-20 and the Semantic Differential (SD). Beyond forest typology, several studies isolate discrete environmental features to assess their incremental contribution to well-being outcomes. The physiological effects of understory vegetation are primarily investigated through autonomic measures such as heart rate and heart rate variability, with additional assessment of blood pressure, electrodermal activity, pupil diameter, gait parameters, EEG activity, and salivary amylase. Psychological outcomes are frequently evaluated using multidimensional instruments—most notably the PANAS-20—alongside targeted measures of restoration (ROS), stress (SSS), anxiety (STAI-S), vitality (SVS), happiness (single-item scales), and frustration (NASA-TLX). Exposure to the shrub layer in virtual forest environments is primarily evaluated through physiological markers, especially heart rate and heart rate variability, followed by electrodermal activity, blood pressure, and EEG-derived indices of brain activity. Less frequently, studies incorporate measures such as blood volume pulse, prefrontal oxygenation, pupil diameter, respiratory rate, salivary amylase, and skin temperature. Psychological outcomes are primarily assessed using multidimensional instruments—including the Feeling Scale (FS) and the Physical Activity Enjoyment Scale (PACES) in physical activity contexts—alongside targeted measures of stress (Short Stress State Questionnaire, SSSQ; Perceived Stress Scale, PSS), restoration (Restoration Components Scale, RCS; Perceived Restorativeness Scale, PRS), anxiety, mindfulness, and relaxation (RRS), as well as single-item indicators. When water is present, physiological assessments focus primarily on heart rate and heart rate variability, followed by blood pressure, electrodermal activity, and salivary amylase. Blood volume pulse and respiratory rate are less frequently examined. Psychologically, studies mainly employ multidimensional tools and single-item measures (excluding happiness). Isolated dimensions such as anxiety, restoration, frustration, and mindfulness are explored, whereas stress and vitality are not investigated. In scenarios featuring deadwood, physiological responses are primarily assessed through heart rate, heart rate variability, and electrodermal activity, while blood pressure and EEG are examined less frequently. Psychological outcomes are predominantly evaluated using multidimensional instruments (PANAS-20, POMS-37), followed by the STADI-S, the Circumplex Model of Emotion, and the Subject's Emotional State scale. Additional measures address stress (PSS-10, SSSQ, single-item scales), relaxation, mindfulness, happiness, and restoration.

Structural variables, such as canopy density, understory vegetation cover (UVC), understory vegetation height (UVH), average tree height, tree diameter, and visual permeability, were only investitaged employing physiological measures. EEG is employed across all levels of canopy density, tree height, tree diameter, and UVC. In contrast, visual permeability and all levels of UVH are evaluated exclusively through pupil diameter. For moderate-to-high UVC and both the lowest and highest levels of canopy density, both EEG and pupil diameter are recorded. The integration of auditory, olfactory, and haptic stimuli expands the scope of virtual forest research beyond visual attributes. The physiological effects of auditory stimuli are predominantly evaluated through autonomic measures, particularly heart rate, heart rate variability, and electrodermal activity. Additional physiological indices include blood pressure, blood volume pulse, respiratory rate, skin temperature, and electroencephalography (EEG), whereas salivary amylase, prefrontal oxygenation, and pain perception are only occasionally assessed. The psychological impact of sound is examined using nearly all identified instruments (37 out of 42), with the PANAS-20 emerging as the most frequently applied measure. The only tools not employed in this context are the Brief Profile of Mood States (BPOMS-30), the Profile of Mood States (POMS-30), the Pleasure–Arousal–Dominance (PAD) model, the Subject's Emotional State scale, and the six-item version of the State–Trait Anxiety Inventory (STAI-S-6). Across studies investigating olfactory stimuli, electrodermal activity represents the core physiological measure, systematically recorded and often complemented by skin temperature, blood volume pulse, electroencephalography (EEG), heart rate variability, and respiratory rate. The psychological impact of olfactory exposure is examined through the Semantic Differential (SD), the Relaxation Rating Scale (RRS), and the 20-item version of the State–Trait Anxiety Inventory (STAI-S-20). Research on the effect of haptic stimuli assesses physiological responses through blood volume pulse, electrodermal activity, heart rate variability, respiratory rate, and skin temperature. In contrast, the psychological dimension is restricted to relaxation, evaluated exclusively using the Relaxation Rating Scale (RRS).

4. Discussion

This review identifies and analyzes the forest characteristics represented in virtual reality (VR) studies and the methodologies used to evaluate their physiological and psychological effects, with the aim of providing a comprehensive foundation for future research. Compared with previous studies, such as Clark et al. (2023), which examined the effects of real forest characteristics on mental health, and Paletto et al. (2025), which analyzed forest-based practices aimed at enhancing human well-being, as well as investigations by Gentile et al. (2023), Abdullah et al. (2021), Gaekwad et al. (2023), and Riches et al. (2021) focusing on specific psychological outcomes, to the best of our knowledge, this review is the first to systematically examine how specific forest characteristics represented in VR environments relate to physiological and psychological indicators of human well-being.

The VOSviewer analysis highlights a concentrated interest in the psychophysical effects of both real and virtual natural environments. It also reveals a strong focus on mental health and wellbeing linked to natural and VR contexts, as well as cognitive and emotional responses in general environments. Furthermore, the analysis of the country network demonstrates a wide global distribution of these research interests, with the USA occupying a central position, followed by China and Taiwan. The textual analysis reveals four key findings emerging from the reviewed literature. First, we found a predominance of broadleaf forest settings, whereas coniferous and mixed forests are less frequently represented. Studies utilizing broadleaf forests are primarily concentrated in Asia, followed by Europe and the United States. Although the existing literature on real forests indicates that mixed forests are the most preferred setting by visitors, a minority of VR studies explore mixed forest stands (Pelyukh et al., 2019a; Notaro et al., 2025). This is relatively surprising, because personal preferences are linked to well-being, especially from a psychological perspective. One possible explanation might be the technical complexity of modeling and rendering performance in VR (Bao et al., 2012), as mixed forests can be more challenging to recreate due to species variety. However, this does not explain the widespread preference for broadleaf settings over coniferous, considering that broadleaf trees generally require more complex modeling (Jun and Zheng, 2009; Zhang et al., 2010). Another explanation might be geographic convenience, which is sometimes mentioned across selection criteria (Li et al., 2020, 2023; Mostajeran et al., 2023; Qi et al., 2022). Further VR research should explore mixed forest settings more accurately to better match individual preferences with objective measures of well-being.

Second, many VR studies do not explicitly describe forest characteristics beyond the traditional classification of forest types (broadleaf, coniferous, or mixed). When the goal of a study is to provide evidence-based suggestions for forest management, visual forest characteristics should be clearly defined. There are in particular three forest characteristics that should be further investigated in future VR studies, namely understory vegetation layers, canopy density, and deadwood.

Concerning understory layers, a substantial part of the literature links shrubs and understory vegetation to visitor well-being, recreational preferences, and aesthetic appreciation in forest environments (Clark et al., 2023; Simkin et al., 2021; Nielsen et al., 2018; Výbošťok et al., 2024). However, fewer than half of the VR studies include shrub and understory layers. Although the technical challenges associated with recreating understory vegetation in virtual environments may partly explain this limitation, further research is needed to better understand their role in shaping well-being outcomes. With respect to forest density in virtual reality (VR) settings, only five of the reviewed VR studies provide information on *dense forests*, and only one examines *open forests* without specifying the density level. This limited number of VR-based investigations of forest density adds to the mixed evidence reported in real-world forest studies regarding visitor preferences and psychophysiological responses to canopy density (Petucco et al., 2018; Pelyukh et al., 2019a; der Wal et al., 2014). Among the VR studies reviewed, only Li et al. (2023) and Guo et al. (2024) explicitly compare different levels of forest permeability and density. The VR experiment conducted by Li et al. (2023) focused on pupil diameter and visual perception, showing that dense canopies, dense understories, and low visual permeability increased pupil diameter—possibly indicating higher alertness or stress—and reduced perceived safety and pleasantness. By contrast, the VR-based study by Guo et al. (2024), which examined brain activity and landscape preferences, found a preference for forests with a higher number of trees and shrubs but moderate canopy density. These results suggest that further VR experiments could help clarify existing inconsistencies by systematically testing how different levels of forest density affect well-being outcomes. Several environmental characteristics correlated with forest canopy density have been included more frequently in VR-based physiological studies than in psychological studies, including UVC/UVH levels, visual permeability, canopy and arbor density, and tree height and diameter. This pattern is noteworthy, as factors such as available light and the perceived openness of a forest may influence individuals' emotional responses, for instance, through perceptions of safety (Grilli et al., 2020).

In relation to deadwood, the literature suggests that certain levels of deadwood contribute to the recreational value of a forest environment. However, preferences vary. Some studies report positive aesthetic perceptions of deadwood (Qiu et al., 2021; Meo et al., 2024), while others indicate a preference for moderate to low amounts (Bayraktar et al., 2024; Ebenberger and Arnberger, 2019; Paletto et al., 2024b), or even its complete absence (Pelyukh et al., 2019b). Despite this interest in real-world studies, deadwood remains an overlooked element in the forest VR literature.

Another open question about the visual dimension of VR studies regards the inclusion of non-forest elements into the forest environment, especially water components. Water elements (rivers or lakes) reinforce the restorative potential of natural environments and positively influence landscape preferences (Yin et al., 2023; White et al., 2010; Notaro et al., 2025). However, fewer than half of the examined studies include virtual forest scenarios featuring water. Among them, Hsieh et al. (2023) investigated the effects of varying water sound levels, and Wang et al. (2019) confirmed the effectiveness of water landscapes in forest resting areas for stress recovery. Other studies (Browning et al., 2020; Moosavi et al., 2024; Chirico et al., 2018) acknowledge the evocative value of water, although it is not examined as a central element of their analysis. In some cases, water was included in scenarios without specific justification. An exception is Yu et al. (2020), whose study, while not explicitly focused on water, qualitatively found that environments containing water were perceived as more restorative.

Third, an important result concerns the non-visual inputs and, more generally, the multisensorial dimension of VR studies. In real forest environments, stimulation engages multiple senses, including sight, hearing, smell, and touch. Consequently, when studying the beneficial effects of forests in a laboratory setting, it is essential to employ scenarios that approximate this multisensory experience as closely as possible. In this review we found that olfactory and tactile inputs are rarely integrated into forest VR experiments, most likely due to the technical and practical challenges associated with their reproduction (de Paiva Guimarães et al., 2022; Tang et al., 2024; Aziz et al., 2020; McAnally and Wallis, 2022).

Sound *stimuli* are the non-visual characteristic most frequently integrated into virtual scenarios, much more than haptic and olfactory *stimuli*. The literature widely associates natural sounds—particularly birdsong, water, and wind—with positive well-being outcomes (Yana and Maeno, 2020; Iyendo, 2017). Their inclusion in virtual experiences effectively enhances realism and psychological benefits. Hsieh et al. (2023) demonstrated that varying intensities of water sounds produce distinct benefits for mood and physiological stress reduction. Moosavi et al. (2024) focused on auditoryenvironmental coherence, showing that natural sounds in chaotic urban contexts reduced stress indicators, whereas urban noise in natural settings had the opposite effect. Similarly, Qi et al. (2022) found that combining birdsong with visual natural elements yielded superior restorative outcomes.

Only a minority of studies have incorporated multiple non-visual *stimuli* into virtual scenarios but all are informative. One example is the work by Qi et al. (2022), who introduced natural scents alongside visual and auditory stimuli and found enhanced restorative effects. Another exception is offered by Hedblom et al. (2019), who found that multisensory combinations helped reduce physiological stress. Lopes et al. (2022) found that the simultaneous inclusion of visual, auditory, haptic, and olfactory *stimuli* produced stronger relaxation effects than visual-only experiments. However, the integration of olfactory stimuli does not always enhance the experience and may sometimes lead to adverse effects, for example, when combined with sound in the absence of visual stimuli (Qi et al., 2022).

Fourth, an important finding concerns the selection of psychological and physiological indicators used in VR studies. Many studies reproduce real-forest designs by adopting the same indicators. These include common cardiovascular indicators such as heart rate (HR), heart rate variability (HRV), and blood pressure (BP), together with other physiological measures such as brain activity (EEG), skin temperature, and electrodermal activity. However, VR experiments also include several parameters that are rarely measured in real forest studies, such as posture and gait metrics, prefrontal oxygenation, pupil diameter, and respiratory rate. A possible explanation is that a lab setting facilitates data collection on these measures. For example, gait and posture can be measured more precisely in a controlled lab than in a forest setting, where slopes and uneven terrain might interfere with measurements. This is another argument to support further VR investigations in the future.

In contrast, salivary cortisol, a frequent indicator in real forest research, does not appear in the reviewed VR literature. This absence is likely because cortisol represents a slower physiological stress response compared to alpha-amylase (Maruyama et al., 2012), making it less suitable for brief VR experiments. Other indicators absent from the VR context include urine and blood analyses, such as testing for dopamine and adrenaline in urine (Li et al., 2011) or natural killer (NK) cells and malondialdehyde molecules in blood (Jung et al., 2015; Mao et al., 2012). However, it is worth noting that such invasive tests are relatively infrequent even in studies conducted in physical environments.

The psychological indicators are, in most cases, self-reported on scales already available in the literature. Therefore, the choice of the assessment tools in VR is highly similar to those used in real forests (Clark et al., 2023; Grilli and Sacchelli, 2020). The most frequently used instruments in VR studies are multi-affective questionnaires, particularly the PANAS and the POMS. Single emotional dimensions are also similar to forest field studies: psychological restoration is the most studied construct, followed by stress, anxiety, vitality, and mindfulness. A difference is that frustration and relaxation appear exclusively in virtual forest studies. Conversely, studies conducted in real forest settings occasionally employ instruments to assess self-esteem, burnout, depression, and general well-being, which have not yet been adopted in VR-based forest research (Clark et al., 2023; Grilli and Sacchelli, 2020). Overall, this review highlights several visual and non-visual elements that future studies could integrate to achieve a more comprehensive understanding of the potential of VR research, as well as its similarities and differences with real-forest studies. In many cases, the ability to replicate forest field studies remains limited by current technological constraints, though this may change as technologies continue to evolve. For example, recent advances in AIgenerated images may facilitate the visual representations of forest characteristics that are currently unavailable or only represented in a limited number of cases.

Lastly, a comment concerns the differences in the information available to participants in VR settings compared to real forests. In real forest environments, characteristics can be easily perceived and identified in the field, whereas in VR they often require explicit explanation. Clear, standardized, and detailed environmental descriptions will therefore be essential in future studies to ensure the accurate identification, comparison, and replication of VR forest characteristics.

Beyond these methodological implications, the findings of this review are also useful for understanding the policy relevance of immersive technologies to promote well-being. In this sense, this review suggests that the practical relevance of VR is not the possibility to replace real forests but to make forest characteristics and forest benefits experimentally visible and comparable with less noise than occurs in real settings. VR produces a clear trade-off between flexibility of forest characteristics manipulation and realism. For this reason, VR should not be interpreted as a substitute for real forest research but rather as a complementary tool. This is especially useful when access to forests is limited by distance, mobility constraints, health conditions, time availability, or institutional settings such as hospitals, schools, care facilities, and workplaces. The policy value of VR-based forest exposure depends on the quality, transparency, and purpose-specificity of the virtual scenarios. Therefore, the main challenge is to design ecologically and environmentally meaningful settings.

5. Conclusion

Virtual reality in forest policy and economics research offers the possibility to investigate the impact of changing forest characteristics on people's psychological and physiological well-being. This benefit comes at the cost of reduced realism, which may hamper the credibility of VR results and their transferability. The uncertainty about VR's potential is increased by the limited number of VR applications and the fact that no guidelines are available for virtual reality studies.

This paper provided a systematic review of immersive VR studies examining the well-being effects of forest exposure. The objectives were to map the forest characteristics represented in virtual environments, to analyse the physiological and psychological indicators used to assess human responses, and to clarify the relevance of this evidence for future research and policy-oriented applications. With respect to the first objective, results suggest uneven patterns of forest characteristics that are represented: broadleaf forests and auditory cues are especially common, while other policy relevant characteristics such as stand density, understory vegetation, and deadwood are still underexplored. A second finding is that current research has focused on stress reduction and restorative potential of forests, but many indicators are heterogeneous and hardly comparable across studies. Third, the reliability of results is challenged by the ability to reproduce ecologically meaningful forest settings.

Overall, VR represents a promising tool for investigating the psychophysiological effects of forest environments, although further methodological developments and more detailed environmental representations will be necessary to fully exploit its potential. In this perspective, VR has the potential to evolve from a purely experimental tool into a decision-support instrument for forest management, contributing to more effective communication, learning, and service innovation in the forest sector (Holopainen et al., 2020).

CRediT authorship contribution statement

Arianna Cerutti: Writing – original draft, Visualization, Investigation, Formal analysis. **Gianluca Grilli:** Writing – original draft, Supervision, Software. **Sandra Notaro:** Writing – original draft, Supervision, Software, Resources, Project administration, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. List of articles included

Table A.1
List of articles included.

AUTHORS	TITLE
Browning et al. (2020)	Can Simulated Nature Support Mental Health? Comparing Short, Single-Doses of 360-Degree Nature Videos in Virtual Reality With the Outdoors
Chan et al. (2023)	Nature in virtual reality improves mood and reduces stress: Evidence from young adults and senior citizens
Chirico et al. (2018)	Designing awe in virtual reality: An experimental study
Davidov et al. (2022)	Effects of Digital Eco-Therapy and Virtual Reality Immersion on Psycho-Emotional State in Different User Groups
Frigione et al. (2022)	An Exploratory Study on the Effect of Virtual Environments on Cognitive Performances and Psychophysiological Responses
Gromala et al. (2015)	The virtual meditative walk: Virtual reality therapy for chronic pain management
Guo et al. (2024)	An empirical study on the response of university students to viewing autumn secondary forest phytocommunities landscape via virtual reality in Northeast China
Hedblom et al. (2019)	Reduction of physiological stress by urban green space in a multisensory virtual experiment
Hong et al. (2019)	The Effects of Watching a Virtual Reality (VR) Forest Video on Stress Reduction in Adults
Hsieh and Li (2022)	Understanding how virtual reality forest experience promote physiological and psychological health for patients undergoing hemodialysis
Hsieh et al. (2023)	The effect of water sound level in virtual reality: A study of restorative benefits in young adults through immersive natural environments
Jones and Wheat (2023)	Green and Pleasant Lands: The Affective and Cerebral Hemodynamic Effects of Presence in Virtual Environments During Exercise
Li et al. (2020)	Effects of brightness levels on stress recovery when viewing a virtual reality forest with simulated natural light
Li et al. (2023)	An eye-tracking study on visual perception of vegetation permeability in virtual reality forest exposure
Lopes et al. (2022)	Nat(UR)e: Quantifying the Relaxation Potential of Ultra-Reality Multisensory Nature Walk Experiences
Masters et al. (2022)	Virtual Nature: Investigating The Effect of Biomass on Immersive Virtual Reality Forest Bathing Applications For Stress Reduction
Mattila et al. (2020)	Restoration in a virtual reality forest environment
Moosavi et al. (2024)	The Role of Auditory and Visual *stimuli* in Stress Perception and Sensory Preference within Virtual Environments
Mostajeran et al. (2024)	Analyzing Cognitive Demands and Detection Thresholds for Redirected Walking in Immersive Forest and Urban Environments
Mostajeran et al. (2021)	Effects of exposure to immersive videos and photo slideshows of forest and urban environments
Mostajeran et al. (2023)	Effects of exposure to immersive computer-generated virtual nature and control environments on affect and cognition
Nukarinen et al. (2020)	Physiological and psychological restoration in matched real and virtual natural environments
O'Meara et al. (2020)	Virtual reality nature exposure and test anxiety
Qi et al. (2022)	Comparative study on birdsong and its multi-sensory combinational effects on physio-psychological restoration
Reese et al. (2022)	Digital shinrin-yoku: do nature experiences in virtual reality reduce stress and increase well-being as strongly as similar experiences in a physical forest?
Riem et al. (2021)	The effect of visual field manipulations on standing balance control in people with multiple sclerosis
Riem et al. (2022)	Visual oscillation effects on dynamic balance control in people with multiple sclerosis
Seabrook et al. (2020)	Understanding how virtual reality can support mindfulness practice: Mixed methods study
Wang et al. (2019)	The influence of forest resting environments on stress using virtual reality
Yu et al. (2020)	Restorative effects of virtual natural settings on middle-aged and elderly adults
Yu et al. (2018)	The effect of virtual reality forest and urban environments on physiological and psychological responses
Yuan et al. (2022)	The Restorative Effects of Virtual Reality Forests on Elderly Individuals during the COVID-19 Lockdown
Zhang et al. (2023a)	The restorative effects of short-term exposure to nature in immersive virtual environments (IVEs) as evidenced by participants' brain activities
Zhang et al. (2023b)	Forestlight: A Virtual Reality Respiratory Biofeedback System Using Interactive Lighting for Pressure Relief

Appendix B. VOSviewer bibliometric data

Table B.2
VOSviewer. Number of links (L), TLS and number of articles by country.

COUNTRY	N. Articles	L	TLS
China	9	2	3
USA	8	5	6
Taiwan	5	3	5
Germany	4	1	1
Canada	3	2	2
Finland	3	2	2
Singapore	2	2	2
Sweden	2	2	2
Italy	2	0	0
Brazil	1	1	1
France	1	1	1
Hong Kong	1	1	1
Australia	1	0	0
Ireland	1	0	0
Russian Federation	1	0	0
South Korea	1	0	0
UK	1	0	0

Table B.3
VOSviewer. Number of links (L), TLS and number of occurrences (O) of keywords.

KEYWORDS	O	L	TLS
Cluster 1 – RED			
humans	11	23	81
forests	8	24	63
adult	7	22	59
female	7	22	67
male	7	22	67
physiology	6	25	61
controlled study	5	20	48
environment	4	18	33
human experiment	4	22	47
urban area	4	18	30
attention	3	17	30
cognition	3	18	24
electroencephalography	3	17	21
immersive virtual environments	3	17	19
Cluster 2 – GREEN			
virtual reality	29	31	135
forestry	10	27	51
natural environments	5	15	23
immersive virtual reality	4	13	21
stress	4	22	27
affect	3	10	11
health	3	12	16
immersive	3	8	11
mental health	3	19	23
restoration	3	10	16
stress reduction	3	10	13
virtual forest	3	12	14
well being	3	12	16
Cluster 3 – BLUE			
emotions	6	19	35
psychology	5	16	32
blood pressure	4	18	30
forest therapy	3	13	15
heart rate	3	18	29

Appendix C. Legend, forest characteristics and measures

For clarity, appendix_data.xlsx is an Excel file with: (i) a legend of variables; (ii) a table that associates physiological measurements with forest characteristics extracted from the articles, indicating the relative number of occurrences for each variable; and (iii) a similar table concerning psychological measurements.

Table C.4
Forest characteristics and measures associated with the articles.

Authors	Forest characteristics	Physiological Measures	Psychological Measures
Browning et al. (2020)	Broadleaf; Dense forest; Water; Understory; Shrub; Sound *stimulus*	SCL	PANAS-20; PRS-11
Chan et al. (2023)	Mixed non specified; Deadwood; Understory; Shrub; Sound *stimulus*	HR; HRV	PANAS-20; Happiness single item; Stress single item
Chirico et al. (2018)	Broadleaf; Water; Sound *stimulus*		PANAS-20; Single item of AWE, Anger, Disgust, Fear, Pride, Sadness, Amusement and Joy
Davidov et al. (2022)	Coniferous; Deadwood; Shrub	EEG	Subject's emotional state
Frigione et al. (2022)	Broadleaf; Water; Sound *stimulus*	SCL; HR; RR	Stress single item; Relax single item
Gromala et al. (2015)	Mixed non specified; Sound *stimulus*	NRS for pain	
Guo et al. (2024)	Broadleaf; Mixed non specified; Low canopy density (0.5, 0.6]; Moderate canopy density (0.6, 0.7]; High canopy density (0.7, 0.8]; Highest canopy density (0.8, 0.9]; Sparse arbor density; Moderate arbor density; Dense arbor density; Short average height; Tall average height; Narrow average diameter; Wide average diameter; Dense forest; Secondary forest; Low UVC (0%, 5%]; Moderate UVC (5%, 25%]; High UVC (>25%); Understory; Shrub;	EEG	
Hedblom et al. (2019)	Mixed 2 species; Urban forest; Not managed; Deadwood; Understory; Shrub; Sound *stimulus*; Olfactory *stimulus*	SCL	
Hong et al. (2019)	Mixed non specified; Understory; Shrub	HR; HRV	PANAS-20; POMS-30; SD
Hsieh and Li (2022)	Mixed 2 species; Secondary forest; Understory; Shrub	HR; HRV	PAD
Hsieh et al. (2023)	Broadleaf; Water; Understory; Shrub; Sound *stimulus*	HR; HRV	STAI-S-20; Affective quality of place
Jones and Wheat (2023)	Mixed non specified; Shrub; Sound *stimulus*	HR; Prefrontal oxygenation	FS; PACES
Li et al. (2023)	Broadleaf; Coniferous; Low canopy density (0.5, 0.6]; Highest canopy density (0.8, 0.9]; Permeability; UVH 0.01 m; UVH 1m; UVH 3m; Moderate UVC (5%, 25]; High UVC (>25%); Dense forest; Not managed; Understory; Shrub	Pupil diameter	
Li et al. (2020)	Mixed 3 species; Urban forest	SCL; BVP	STAI-S-6
Lopes et al. (2022)	Broadleaf; Shrub; Sound *stimulus*; Olfactory *stimulus*; Haptic *stimulus*	EDA; ST; HRV; RR; BVP	RRS
Masters et al. (2022)	Coniferous; Sound *stimulus*		PANAS-20; PRS-16; ZIPERS
Mattila et al. (2020)	Coniferous; Urban forest; Understory; Shrub; Sound *stimulus*		PANAS-20; PRS-16; SVS-6; ROS
Moosavi et al. (2024)	Broadleaf; Water; Sound *stimulus*	HR; HRV; BVP	STAI-S not specified; NASA-TLX
Mostajeran et al. (2023)	Broadleaf; Deadwood; Shrub; Sound *stimulus*		PANAS-20; PRS-12; PSS-10
Mostajeran et al. (2021)	Mixed non specified; Deadwood; Shrub; Sound *stimulus*	GSR; HR	POMS-37; PSS-10; SSSQ; STADI-S-20
Mostajeran et al. (2024)	Sound *stimulus*		PANAS-20; PRS-26

(continued on next page)

Table C.4 (*continued*)

Authors	Forest characteristics	Physiological Measures	Psychological Measures
Nukarinen et al. (2020)	Mixed non specified; Water; Sound *stimulus*	EDA; HR; HRV	PANAS-20
O'Meara et al. (2020)	Coniferous; Water; Deadwood; Understory; Shrub; Sound *stimulus*		PANAS-20
Qi et al. (2022)	Coniferous; Urban forest; Sound *stimulus*; Olfactory *stimulus*	SCL; ST; EEG	STAI-S-20; SD
Reese et al. (2022)	Broadleaf; Urban forest; Understory; Shrub; Sound *stimulus*		PANAS-20; PRS-11; SSS; SVS-6; ROS
Riem et al. (2022)	Understory	Stepping variability; Foot placement; Sensitivity of CoM	
Riem et al. (2021)		CoP frequency response; CoP mean path length	
Seabrook et al. (2020)	Broadleaf; Water; Deadwood; Understory; Shrub; Sound *stimulus*		SMS; Circumplex model of emotion
Wang et al. (2019)	Broadleaf; Mixed non specified; Water; Understory; Shrub	HR; BP; Salivary amylase	BPOMS-30
Yu et al. (2020)	Broadleaf; Dense forest; Open forest; Water; Deadwood; Understory; Shrub; Sound *stimulus*	HR; HRV; BP	RCS; POMS-37
Yu et al. (2018)	Mixed 4 species; Water; Sound *stimulus*	HRV; BP; Salivary amylase	POMS-37
Yuan et al. (2022)	Broadleaf; Dense forest; Not managed; Water; Understory; Shrub; Sound *stimulus*		POMS-30; ROS
Zhang et al. (2023a)	Mixed non specified; Dense forest; Urban forest; Understory; Shrub; Sound *stimulus*	EEG	PANAS-20; PRS-16
Zhang et al. (2023b)	Coniferous; Understory	HR; HRV; RR	PSS-14

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.forpol.2026.103870.

Data availability

No data was used for the research described in the article.

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