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SOLUÇÕES BASEADAS NA NATUREZA COMO ESTRATÉGIA DE GESTÃO INTEGRADA DA QUALIDADE, MEIO AMBIENTE, SAÚDE E HIGIENE OCUPACIONAL

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Dissertação apresentada como requisito para a obtenção do título de Mestre em Engenharia Civil e Ambiental da Universidade Estadual Paulista "Júlio de Mesquita Filho", Área de Concentração Saneamento.

Orientador: Prof. Dr. Adriano Bressane

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Resumo

A busca por ambientes de trabalho mais saudáveis, sustentáveis e eficientes tem impulsionado o interesse por Soluções Baseadas na Natureza (SbN) como estratégias inovadoras de gestão integrada da qualidade, meio ambiente, saúde e higiene ocupacional (QMSH). Esta dissertação investiga a aplicabilidade das SbN no contexto ocupacional, combinando o desenvolvimento de ferramentas de suporte à decisão com a consolidação crítica do conhecimento científico. O primeiro eixo do trabalho consistiu na proposição e validação de um Sistema de Suporte à Decisão baseado em lógica fuzzy (SSDF), capaz de recomendar intervenções baseadas na natureza a partir da avaliação de múltiplos indicadores ambientais e ocupacionais. Aplicado em um estudo de caso real, o SSDF demonstrou eficácia no tratamento de incertezas e subjetividades, gerando recomendações adaptáveis que contribuem para a melhoria do bem-estar, da saúde e da produtividade no ambiente de trabalho. O segundo eixo envolveu a realização de uma revisão sistemática da literatura, cujo objetivo foi mapear os benefícios, barreiras e oportunidades associados à implementação de SbN em ambientes laborais. A revisão evidenciou os impactos positivos das SbN na saúde mental, na qualidade ambiental e na satisfação dos trabalhadores, ao mesmo tempo em que identificou desafios relacionados a custos, falta de conhecimento técnico e dificuldades de integração com sistemas de gestão existentes. Em conjunto, os resultados desta dissertação apontam para o grande potencial das SbN na promoção de ambientes ocupacionais mais resilientes e centrados no bem-estar humano, ao mesmo tempo em que reforçam a necessidade de instrumentos práticos, como o SSDF, para apoiar sua adoção efetiva. As contribuições teóricas e aplicadas aqui apresentadas oferecem subsídios para o avanço das práticas de gestão integrada de QMSH e para o fortalecimento da sustentabilidade no ambiente de trabalho.

Palavras-chave: soluções baseadas na natureza; gestão integrada; qualidade ambiental; saúde e higiene ocupacional.

Abstract

The pursuit of healthier, more sustainable, and more efficient workplaces has driven growing interest in Nature-Based Solutions (NbS) as innovative strategies for integrated management of quality, environment, occupational health, and hygiene (QEHS). This dissertation investigates the applicability of NbS in occupational contexts by combining the development of decision-support tools with a critical consolidation of scientific knowledge. The first component of the research involved the design and validation of a Fuzzy Logic-based Decision Support System (FDSS), capable of recommending nature-based interventions based on the evaluation of multiple environmental and occupational indicators. Applied in a real-world case study, the FDSS demonstrated effectiveness in handling uncertainties and subjectivities, generating adaptive recommendations that contribute to improving workplace well-being, health, and productivity. The second component involved a systematic literature review aimed at mapping the benefits, barriers, and opportunities associated with the implementation of NbS in workplace environments. The review highlighted the positive impacts of NbS on mental health, environmental quality, and employee satisfaction, while also identifying challenges related to implementation costs, technical knowledge gaps, and difficulties in integrating NbS into existing management systems. Together, the results of this dissertation demonstrate the significant potential of NbS to promote more resilient and human-centered workplaces, while underscoring the importance of practical tools such as the FDSS to support their effective adoption. The theoretical and applied contributions presented herein offer valuable insights for advancing integrated QEHS management practices and fostering sustainability in occupational environments.

Keywords: Nature-based solutions; integrated management; environmental quality; occupational health and hygiene.

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1 INTRODUÇÃO

De acordo com Gillis (2015), os ambientes construídos pelo homem frequentemente negligenciam a integração de elementos naturais, comprometendo a saúde e bem-estar de seus ocupantes. Nesse contexto, a integração de elementos naturais, como vegetação e materiais orgânicos, em projetos de design biofílico, tem se mostrada promissora para criar ambientes mais saudáveis (LING, 2021). A exemplo, Molina (2020) discute sobre o uso de jardins em ambientes internos de edificações, como alternativa para interação harmoniosa entre a natureza e o meio artificial.

Em um estudo sobre a revitalização do interior de edificações, Sforazzini (2022) destaca o uso de materiais naturais, como gesso de cal hidráulica e fibra de algodão reciclada, como forma de promover conforto. Em outro exemplo, Martinović et al. (2023) enfatiza a importância dessa integração com a natureza, para a sustentabilidade do ambiente construído. Dessa forma, o design biofílico vai além de práticas sustentáveis, criando espaços com potencial de contribuir para o bem-estar dos trabalhadores, reduzindo estresse e aumentando a produtividade.

Nesse contexto, as Soluções Baseadas na Natureza (SbN) emergem como uma abordagem inovadora, possibilitando a combinação de princípios ecológicos com design e engenharia, para criar ambientes saudáveis e sustentáveis (BRESSANE et al., 2024b). Petrova et al. (2022), discute que a implementação de SbN em contextos ocupacionais ainda é pouco estudada, especialmente em relação à sua aplicação como estratégia de gestão integrada da qualidade, meio ambiente, saúde e higiene ocupacional (QMSH). A importância desta integração reside na possibilidade de melhoria da saúde e bem-estar dos trabalhadores, redução do absenteísmo, aumento da produtividade e minimização do erro humano, fatores críticos para a sustentabilidade e eficiência das organizações (Davis et al., 2021; Vasiliev et al., 2022).

A relevância das SbN tem ganhado destaque devido a necessidade de abordagens que promovam a sustentabilidade e o bem-estar nas organizações. Assim, em um ambiente onde as questões ambientais e de saúde ocupacional estão cada vez mais interconectadas, a adoção de SbN oferece uma solução que pode abordar múltiplos aspectos da gestão de QMSH (Petrova et al.,2022).

De acordo com Zhong (2021), a reconexão com a natureza tem sido reconhecida como um dos desafios mais urgentes na arquitetura urbana contemporânea, dado o impacto significativo das construções na saúde e bem-estar humano. Numerosos estudos documentam os benefícios do contato com a natureza para a saúde e o bem-estar humano, incluindo a redução do estresse, melhora da concentração e aumento do moral. Indicando um grande potencial para a sua aplicação em ambientes ocupacionais, contexto que ainda é insuficientemente explorado (Bratman et al. 2019; Zhong, 2021; Bressane et al., 2022; Bressane et al., 2024a; Bressane et al., 2024b).

A exposição a ambientes naturais, como destacado por Bratman et al. (2019), reduz os níveis de cortisol, aliviando o estresse e melhorando o humor geral. Petrova et al. (2022) complementam que SbN podem melhorar significativamente a qualidade ambiental, aumentando os serviços ecossistêmicos, fornecendo estratégias econômicas e eficazes de longo prazo, com impacto direto na qualidade de vida dos trabalhadores.

A literatura existente tem focado predominantemente em espaços públicos e residenciais, negligenciando o potencial transformador das SbN em ambientes laborais. Este projeto de pesquisa busca preencher essa lacuna ao investigar como as SbN podem ser implementadas como uma estratégia de gestão integrada da QMSH em ambientes ocupacionais. Esta integração pode incluir desde a incorporação de áreas verdes internas, até o uso de materiais naturais e a criação de espaços de trabalho ao ar livre (DAVIS et al., 2021; VASILIEV et al., 2022). Espera-se que a inclusão de elementos da natureza nos ambientes de trabalho possa aumentar o tempo e a frequência de contato com tais elementos, mesmo em ambientes fechados, visando impactar positivamente o humor, o sono, os níveis de estresse e o estado psicossocial (Yin, 2020).

Por meio de seus resultados, este estudo espera contribuir para o campo da gestão integrada de QMSH, fornecendo uma base teórica e prática para a adoção de SbN em ambientes ocupacionais. Trazendo os benefícios das SbN e fornecendo diretrizes práticas para sua implementação. Como observado por Alaghbari (2023), a sustentabilidade do ambiente laboral refere-se aos processos seguros e produtivos de acordo com as necessidades ambientais, sociais e futuras. Nesse sentido, a pesquisa poderá orientar políticas públicas e práticas empresariais, incentivando a adoção de SbN desde a concepção de projetos até a gestão contínua do ambiente de trabalho, promovendo um futuro mais sustentável e saudável para os trabalhadores (SCHRÖTER et al., 2022).

Gillis (2015) destaca que a implementação do design biofílico, pode aproveitar a conexão inata dos seres humanos com o mundo natural, melhorando a saúde e bem-estar geral no ambiente de trabalho. Logo, este projeto de pesquisa não só visa preencher lacunas de conhecimento existentes, mas também fornece ferramentas práticas e orientações que possam ser utilizadas por gestores e profissionais de saúde ocupacional para criar ambientes de trabalho que promovam a saúde, a sustentabilidade e a eficiência organizacional (COLLIER; BOURKE, 2022).

2 ESTRUTURA DA DISSERTAÇÃO

Esta dissertação foi organizada na forma de uma coletânea de artigos científicos, cada um abordando dimensões complementares do tema central: o uso de Soluções Baseadas na Natureza (SbN) como estratégia de gestão integrada da qualidade, meio ambiente, saúde e higiene ocupacional (QMSH). A estrutura adotada visa a construir uma linha de raciocínio que parte da proposição de uma solução prática para, posteriormente, contextualizá-la e ampliá-la mediante a análise do estado da arte.

O primeiro artigo apresenta o desenvolvimento de um Sistema de Suporte à Decisão baseado em lógica fuzzy (SSDF). O sistema foi concebido para recomendar intervenções com base em SbN, utilizando indicadores de conforto ambiental e saúde ocupacional. Por meio da aplicação de lógica fuzzy, o SSDF é capaz de lidar com as incertezas e subjetividades que caracterizam os ambientes de trabalho reais. A aplicação prática do sistema, em um estudo de caso em um espaço de coworking, permitiu validar sua eficácia e discutir suas potencialidades e limitações, evidenciando sua contribuição inovadora para a gestão integrada de QMSH.

O segundo artigo realiza uma revisão sistemática da literatura, investigando os benefícios, barreiras e perspectivas para a implementação de SbN em ambientes ocupacionais. Essa revisão amplia a base teórica sobre o tema, sistematizando evidências de como o contato com elementos naturais pode impactar positivamente a saúde, o bem-estar e a produtividade dos trabalhadores. Além disso, identifica lacunas relevantes no conhecimento e nos métodos de implementação de SbN, fornecendo um panorama crítico que fundamenta a necessidade de ferramentas como o SSDF desenvolvido.

Esses dois artigos se articulam de maneira complementar: enquanto o primeiro propõe e valida uma ferramenta prática de apoio à decisão, o segundo consolida o arcabouço teórico que justifica e potencializa a aplicação de SbN no contexto ocupacional. Assim, a dissertação constrói uma trajetória que parte da inovação metodológica para, em seguida, embasá-la cientificamente, contribuindo para a promoção de ambientes laborais mais saudáveis, resilientes e sustentáveis.

3 OBJETIVOS

3.1 Objetivo Geral

Analisar criticamente o papel das Soluções Baseadas na Natureza (SbN) como estratégia integrada para promoção da qualidade ambiental, saúde e bem-estar no ambiente ocupacional, por meio da sistematização do conhecimento científico e do desenvolvimento de um sistema de suporte à decisão baseado em lógica fuzzy.

3.2 Objetivos específicos

- Revisar sistematicamente a literatura científica sobre a aplicação de SbN em ambientes ocupacionais, identificando seus benefícios, desafios e lacunas na gestão integrada da qualidade, meio ambiente, saúde e higiene ocupacional.
- Desenvolver um Sistema de Suporte à Decisão Fuzzy (SSDF) para recomendar intervenções baseadas na natureza em ambientes de trabalho, considerando múltiplos indicadores de conforto ambiental e saúde ocupacional.
- Validar empiricamente o SSDF em um estudo de caso real, avaliando sua capacidade de lidar com incertezas e fornecer recomendações robustas e adaptáveis para diferentes condições ocupacionais.

4 ARTIGO PUBLICADO

Enhancing Workplace Health and Wellbeing with Nature-Based Solutions: A Fuzzy System Framework for Evidence-Based Decision-Making

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Abstract: The rise in performance and health concerns presents a complex challenge for workplace well-being. While existing research highlights the positive impact of exposure to nature on well-being, there is a gap in supporting biophilic building design in workplaces. This study seeks to address this issue by introducing a fuzzy framework to recommend Nature-based Solutions (NbS) for enhancing workplace health and well-being. The primary objective of this study is to enhance workplace health and well-being through the integration of NbS, while providing decision-makers with a systematic and evidence-based tool for managing uncertainties inherent in complex workplace environments. The study introduces a framework comprising two fuzzy subsystems addressing environmental comfort and occupational health. A third subsystem integrates the outputs from both antecedent subsystems to recommend NbS for specific workplace conditions. A case study is used to introduce and validate the practical application of the proposed framework. The proposed framework effectively addresses the complexities and uncertainties of workplace health and well-being by providing flexible and targeted recommendations for specific conditions. The NbS recommendations—including green walls, indoor gardens, and natural light filters—contributed to enhanced workplace conditions, reduced absenteeism, and increased employee satisfaction. This proposal demonstrates flexibility in resource allocation for varying workplace conditions. Its recommendations, aligned with NbS principles and addressing uncertainty and diverse variables, enhance its applicability in real-world workplace scenarios, promoting strategic resource use. Key contributions include a novel approach to integrating fuzzy logic with biophilic design principles, offering a robust decision-support tool for workplace health and well-being enhancement.

Keywords: Workplace wellbeing; Environmental health; Nature-based Solutions; Fuzzy logic; Artificial intelligence

1. Introduction

A positive and supportive work environment contributes to greater employee wellbeing and increased performance. The competitive and output-driven nature of certain environments can indeed contribute to escalating stress levels among workers (Aryanti et al., 2020). This heightened stress can have detrimental effects on overall health and wellbeing, ultimately manifesting in increased sick leave cases related to stress, depression, anxiety, and burnout-exhaustion (Gritzka et al., 2020). It underscores the importance of creating a balanced and supportive work environment to mitigate these negative impacts (Rahmey et al., 2022). Aryanti et al. (2020) emphasize that environmental conditions are a key factor influencing workers' wellbeing. Indoor environmental quality holds particular significance in workplaces, with studies indicating that exposure to nature indoors positively impacts occupants' performance and wellbeing (Sadick and Kamardeen, 2020).

Biophilic Design (BD) integrates Nature-based Solutions (NbS), offering an alternative approach to promote workplace health and wellbeing. Acknowledged as a sustainable strategy, it embeds nature into human infrastructure, categorizing natural design features within established design frameworks. Despite the acknowledged importance of BD, Lei et al. (2022) argue for further research to develop biophilic guidelines and assessment methods tailored to building typologies. In the quest to establish healthier and more sustainable built environments, NbS takes on a specific connotation, often termed a nature-based intervention. This involves engaging individuals in natural settings with the aim of enhancing health-related outcomes throughout their lives (Lipponen et al., 2022). Past research has consistently demonstrated the positive impact of nature exposure on health and wellbeing across diverse occupational settings.

Workplace health and wellbeing encompasses multiple facets of the work environment, spanning from the adequacy and security of physical surroundings to employees' perceptions of their tasks, the workplace atmosphere, and organizational structure (International Labour Organization, 2023). In this context, workplaces frequently face challenges affecting occupational health, including issues like poor air quality, insufficient daylight exposure, and a lack of connection to nature. In alignment with this, Gilchrist et al. (2015) underscore the significance of integrating landscape and building design in workplace planning, recognizing that greenspace functions extend beyond aesthetics. Richardson et al. (2017) emphasizes the importance of this integration as a new paradigm for ergonomics, underlining the significance of considering the integrative nature of human experience and the connection between wellbeing and nature. The implications of these factors go beyond comfort, significantly impacting the overall wellbeing and productivity of individuals within these environments. Consequently, there is an urgent need to systematically address these challenges.

The primary motivation for this study arises from the need to address the critical gap in systematically integrating biophilic design with decision-making tools to improve workplace health and well-being. The goal is to empower decision-makers with a framework capable of handling the complexities and uncertainties inherent in workplace environmental and occupational health conditions. This work contributes by proposing a novel framework that integrates fuzzy logic with biophilic design principles to systematically recommend NbS, offering practical, scalable, and resource-efficient solutions for workplace improvement.

The present study proposes an innovative framework by utilizing a Fuzzy Decision Support System (FDSS) to recommend NbS capable of enhancing workplace health and wellbeing. The novelty lies in the integration of fuzzy logic with biophilic design principles, which allows for the accurate handling of uncertainties inherent in complex decision-making processes related to environmental and occupational health indicators. This framework stands out by offering a systematic and quantifiable approach to improving workplace conditions through NbS, addressing both theoretical and practical aspects.

Through a review of related works and a case study, the study establishes the groundwork for the practical application of the proposed FDSS as a tool for decision-makers in the field of biophilic design. This article comprises four key sections: "Related works" reviews prior research for context. The "FDSS framework modeling" section details the architecture and integration of fuzzy components in the decision support system. In the "Case study" section, practical validation demonstrates real-world applicability. The "Concluding remarks" section encapsulates study findings and implications. Key contributions include the development of a robust decision-support tool that integrates fuzzy logic with biophilic design principles, providing flexible and scalable solutions for enhancing workplace health and well-being.

2. Related Works

To search for the most reliable, relevant, and up-to-date related works, ScienceDirect, Scopus, and Web of Science databases were used, applying the following query: title-abs-key (“building” or “project” or “design”) and (“green” or “biophilic” or “nature-based solution”) and (“occupational health” or “workplace” or “worker's health”) and (“artificial intelligence” or “fuzzy” or “decision support”) and (limit-to (pubstage, “final”)) and (limit-to (doctype, “ar”)) and limit-to (subjarea, “eng.” or “env.”)) and (limit-to (pubyear, “from 2014 to 2023”)) and (limit-to (language, “english”)). This search resulted in 261 articles, which were preliminarily screened. After excluding those outside the scope, 17 articles were selected and discussed below.

Research on the influence of natural environments in the workplace has demonstrated considerable potential for enhancing employee well-being. For instance, Sahlin et al. (2014) conducted a 12-week nature-based stress management program involving 33 female participants. The study revealed significant reductions in burnout scores, decreases in long-term sick leave, and improvements in work ability. Gardening activities and interactions with nature emerged as pivotal components for stress alleviation and fostering effective coping mechanisms. Similarly, Gilchrist et al. (2015) explored the impact of natural views—such as trees, lawns, and flowering plants—in workplace environments. Their study of 366 employees highlighted positive correlations between access to green spaces, visual exposure to vegetation, and self-reported well-being. These findings emphasize the importance of integrating green settings into architectural designs to enhance restoration and promote employee well-being.

Gritzka et al. (2020) conducted a systematic review assessing the efficacy of workplace nature-based interventions (NBIs) on employees' mental health and overall well-being. The review categorized outcomes into five domains: (i) mental health indices, (ii) cognitive abilities, (iii) recovery and restoration, (iv) work and life satisfaction, and (v) psychophysiological indicators. While the synthesis demonstrated consistently positive effects on mental health and cognitive functioning, results for recovery and restoration were mixed, indicating that research on NBIs in authentic workplace contexts is still at a nascent stage.

Contrasting findings are evident in the works of Korpela et al. (2017) and Miles et al. (2017). Korpela et al. (2017), in a longitudinal study involving 841 employees, examined the relationship between different types of nature exposure—such as window views, indoor plants, and outdoor activities—and employee well-being over a one-year period. The study found that physical activity in natural environments during leisure time significantly enhanced vitality, whereas workplace-based nature exposure did not yield a measurable impact on well-being. Conversely, Miles et al. (2017) provided evidence supporting the beneficial effects of natural environments on workplace health, including reductions in illnesses, improvements in mood, and enhanced mental well-being.

Reinforcing the relevance of nature exposure, Gonçalves et al. (2023) conducted a systematic review focusing on biophilic workplace designs and nature exposure during working hours. Analyzing 16 studies, the review revealed that biophilic office environments positively influence well-being, motivation, job satisfaction, and performance. However, it also identified notable research gaps, underscoring the need for comprehensive, multidimensional investigations to better inform design strategies and foster healthier, more productive workplaces.

The significance of integrating nature in workplace settings is further supported by Sadick and Kamardeen (2020), who consolidated evidence on the effects of indoor nature exposure. Their findings highlight that indoor nature exposure improves health and motivation, contributing to social sustainability, while outdoor exposure supports economic and environmental sustainability by promoting restoration and stress reduction. The authors advocate for a holistic approach that combines indoor and outdoor nature integration in workplace design.

Kearney et al. (2023) investigated the influence of physical work environments on retail employees, examining stimuli such as color, design, cleanliness, odor, music, lighting, and layout. Their findings validated a holistic construct of environmental perception, indicating that these stimuli significantly affect employee satisfaction and loyalty. This underscores the critical role of thoughtful environmental planning in enhancing workplace satisfaction.

In a related context, Doloksaribu et al. (2022) examined the interplay between psychological well-being and organizational climate on job satisfaction among employees of Indonesia's National Road Implementation Unit. Their regression analysis demonstrated that these variables accounted for 88.9% of the variance in job satisfaction, highlighting the importance of addressing psychological and physical workplace factors to improve employee outcomes. Msuya et al. (2023) extended this understanding by exploring transformational leadership and organizational support in Tanzanian higher learning institutions. Their findings emphasized that leadership styles significantly influence employee well-being, with perceived organizational support mediating this relationship.

Building on these insights, Putra et al. (2024) conducted a comprehensive review identifying psychosocial relationships, job satisfaction, and social support as key determinants of workplace well-being. The review highlighted the role of organizational culture and employee engagement in fostering wellness, advocating for deeper investigations into these dynamics.

Studies on BD and its implications for workplace health underscore its transformative potential. Khanehshenas and Habibi (2020), through a systematic review, linked BD to enhanced well-being, performance, and stress reduction. Similarly, Lei et al. (2022) examined BD attributes in green office settings in Singapore and Shenzhen, revealing positive evaluations of BD's contributions to health and well-being. Proactive approaches to workplace well-being have also been explored. For instance, Ilies et al. (2024) discussed how employees can enhance their well-being through strategies like savoring positive experiences, while Zhang et al. (2023) highlighted the role of environmental identity and nature connectedness in promoting well-being.

These findings collectively underscore the transformative potential of nature-based solutions in workplaces. However, they also reveal a pressing need for innovative tools to address uncertainties in decision-making regarding well-being interventions. Addressing this gap, our study introduces a FDSS tailored to optimize workplace well-being through nature-based strategies.

3. Theoretical Framework

3.1 Concept of Nature-Based Solutions

NbS are defined as strategies inspired by natural processes to address societal challenges while benefiting human well-being, biodiversity, and ecosystem services (Batista et al., 2024). In workplace contexts, NbS includes interventions like green walls, biophilic design, and natural light optimization, aimed at enhancing environmental and occupational health (Andreucci et al., 2021). Recent studies emphasize their role in mitigating stress, enhancing air quality, and fostering employee satisfaction (Tiwari et al., 2022). The application of NbS within workplace environments has been linked to improvements in psychological and physiological well-being. For instance, Rastkhadiv et al. (2024) observed enhanced mental health outcomes in workplaces integrating green spaces, while Zhang et al. (2023) highlighted how NbS promotes restorative environments conducive to productivity and motivation. These findings support the integration of NbS in workplace design to address environmental and organizational challenges systematically.

3.2 Fuzzy Logic in Decision-Making

Fuzzy logic is a mathematical approach to handling uncertainties and ambiguities inherent in real-world problems (Zadeh, 1965). Its ability to process imprecise data makes it particularly suitable for workplace decision-making, where variables such as comfort and health are subjective. The integration of fuzzy logic into NbS frameworks has been validated through its application in other fields, such as urban planning and environmental engineering (Oyefusi et al., 2024). Studies on fuzzy systems underscore their efficacy in combining diverse and uncertain data inputs to generate actionable insights. For example, Spalding et al. (2022) demonstrated the utility of fuzzy systems to forecast student performance and retention risk in engineering education, while Goulart et al. (2023) applied fuzzy models for coagulant dosage in drinking water treatment plant builds on this foundation, offering a structured approach to deal with uncertainties in complex systems.

3.3 Integration of Biophilic Design and NbS

Biophilic design, a concept that integrates nature into built environments, complements NbS by focusing on human-nature connections (Kellert et al., 2008). Studies like those by Gertik and Karaman (2023) show that biophilic workplaces enhance employee well-being, reduce absenteeism, and boost creativity. Furthermore, Gao et al. (2023) observed that biophilic elements like natural light and vegetation significantly improved environmental satisfaction and overall health. The incorporation of fuzzy logic into biophilic design frameworks represents a novel approach to addressing the variability in individual preferences and workplace conditions. Oyefusi et al. (2024) employed the Fuzzy Analytical Hierarchical Process to evaluate NbS in construction, showcasing the synergy between fuzzy logic and NbS for workplace enhancement.

3.4 Bridging Literature and Model Development

While prior studies establish the efficacy of NbS and biophilic design in promoting workplace well-being, a systematic connection between theoretical findings and practical implementations has often been lacking. The FDSS addresses this gap by integrating empirical data with expert-driven rules to recommend context-specific NbS interventions. This approach aligns with the evidence-based methodologies advocated by Stigsdotter et al. (2024). By synthesizing principles from NbS, biophilic design, and fuzzy logic, the proposed FDSS framework offers a robust tool for improving workplace well-being. Its foundation in recent literature ensures theoretical and practical coherence, bridging gaps in current research and application.

4. FDSS Modeling

A FDSS can be modeled through the definition of input and output variables, membership functions, fuzzy rules, and an inference engine (Bressane et al., 2020, 2024a).

4.1. Input and Output Variables

In this study, while output variables recommend NbS for improving workplace health and wellbeing, the following input variables represent occupational health and environment quality indicators, which were selected from the related works review:

- Thermal comfort directly influences occupants' wellbeing, affecting productivity and overall comfort (Bueno et al., 2021). Environments with appropriate temperatures contribute to more efficient daily activities.
- Excessive noise can induce stress and distraction, negatively impacting mental health and concentration (Lee and Aletta, 2019; Naylor et al., 2019). Acoustically comfortable environments are crucial for productivity and wellbeing.
- Proper lighting is essential for visual and mental health (Sithravel and Ibrahim, 2021). Well-lit spaces not only enhance visual efficiency but also influence the circadian rhythm, affecting sleep and mood.
- Absenteeism reflects how often employees miss work due to health issues (Bartels et al., 2019; Medina-Garrido et al., 2020; Litchfield, 2021). Solutions that enhance occupational health can reduce absenteeism, contributing to uninterrupted operations.
- Evaluating hazardousness involves identifying and mitigating occupational risks (Narocki, 2021; Oakman et al., 2022).
- Unhealthiness is related to conditions harmful to health (Wallace, 2019). Solutions addressing unhealthy factors, such as air pollutants, contribute to a healthier work environment.

The selection of comfort indicators and occupational indicators prioritizes measurable, actionable variables with a direct impact on workplace health and well-being. These variables were chosen due to their:

- Documented Impact: Extensive evidence supports their critical role in influencing workplace outcomes, such as productivity, health, and satisfaction. For instance, Bueno et al. (2021) and Lee & Aletta (2019) highlight the substantial impact of temperature and noise on cognitive function and mental health. Similarly, Sithravel & Ibrahim (2021) emphasize the significance of lighting on visual and mental health, linking it to improved circadian rhythm and mood regulation. These indicators represent areas with a well-established connection to both physical and mental workplace outcomes.

- Practicality and Actionability: These variables are directly modifiable through Nature-based Solutions (NbS), aligning with the study's focus on environmental and occupational health interventions. For example, NbS can effectively enhance thermal comfort, reduce noise, and optimize lighting through biophilic designs and other environmental adjustments.
- Quantifiability: They offer clear, standardized metrics suitable for inclusion in a fuzzy decision support system (FDSS), ensuring reliable, data-driven recommendations that can be practically implemented in workplace settings.

While psychosocial indicators (e.g., job satisfaction, workload) and labor conditions (e.g., work schedules, policies) are undeniably significant, their exclusion was intentional. These variables, though impactful, are subjective and heavily influenced by organizational culture and individual perceptions, making them less compatible with the FDSS's quantifiable framework. Furthermore, addressing these aspects typically requires broad organizational changes and policy shifts, which extend beyond the scope of NbS-focused interventions.

Additionally, while ventilation and moisture are recognized as critical to environmental quality, they were excluded due to project parameters and inconsistent data availability across the case studies reviewed. However, their effects are indirectly captured through broader variables such as hazardousness and unhealthiness, which encompass a range of workplace environmental risks and conditions.

By emphasizing thermal comfort, acoustical quality, lighting, absenteeism, hazardousness, and unhealthiness, the FDSS achieves a balanced approach. It addresses key factors that are both relevant and feasible within the scope of the study, ensuring actionable and impactful insights for improving workplace health and well-being.

4.2. Membership Functions

To accurately quantify and handle the ambiguity of information in the Fuzzy System Framework for Biophilic Design, fuzzy logic is employed due to its proficiency in managing imprecise and subjective data (Bressane et al., 2024b). Unlike classical logic with binary membership functions, fuzzy logic expresses membership (φ) on a continuous interval from 0 to 1 (Mochizuki et al., 2016; Spalding et al., 2022). Various functions, such as linear, sigmoid, and quadratic, may be used to quantify the degree of pertinence within modeled concepts (Biagolini et al., 2017; Zwirn et al., 2024). The proposed FDSS employs triangular-shaped membership functions for concepts modeling (Figure 1).

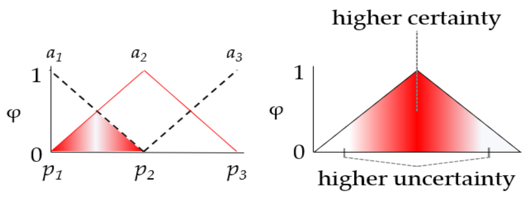

Figure 1. Triangular-shaped membership functions for concepts modeling.

The continuous membership interval enables an accurate representation of partial truth within linguistic values, whose varying intervals are delimited by parameters (p) defining regions of certainty and uncertainty. In turn, linguistic values (a_i) related to the input variables represent is introduced as levels of quality (a_1 = low, a_2 = medium, a_3 =high).

In the proposed framework, fixed values for such parameters (p) are not proposed, as they should vary according to the specificities of each case (see case study). For instance, in an office building setting, the accepted noise level will not be the same as that allowed in the operational sector of a factory. So, the domain of each variable has been standardized to a continuous range between 0 and 1 using the Min-Max scaling method, which rescales the range of features to scale the range in [0, 1]. This method was chosen to maintain consistency across different types of environmental and health indicators by transforming the data into a comparable scale without distorting differences in the ranges of values. For the average value (highlighted in red in Figure 1), the triangular-shaped membership function parameters have been defined as follows: p_1 at 0 representing the minimum value of the input range, p_2 at 0.5 representing the midpoint, and p_3 at 1 representing the maximum value of the input range. This enabling a more flexible and realistic treatment of uncertainties—a fundamental aspect of fuzzy logic for modeling real-world phenomena (Goulart et al., 2023).

4.3. Fuzzy Rules and Inference Engine

Practical applications of this theory involve using fuzzy rules to define the link between variables, mapping inputs to outputs (Bressane et al., 2024b). Fuzzy rules define the link between variables, mapping inputs to outputs. The inference engine applies these rules using fuzzy logic operators of conjunction (minimum, product, Lukasiewicz, other) and disjunction (sum, maximum, for instance), which are applied to build relational propositions (IF-THEN). The Type-1 Mamdani inference engine, also known as the Max-Min method, was employed in this study to derive recommendations from the fuzzy rule sets. This approach involves the application of fuzzy logic to handle imprecision and uncertainty by applying rules that combine inputs through fuzzy conjunctions and implications (Novitzká et al., 2022). The Max-Min method specifically operates by taking the minimum value of the input variables for the 'AND' condition and the maximum value for the 'OR' condition in the rule's antecedent, thus producing a fuzzy set (Setia, 2019). The resulting fuzzy outputs are then defuzzified using the centroid method to provide crisp recommendations, which have been validated for their applicability in various fields like intelligent systems and engineering applications (Novitzká et al., 2022). This process allows for a more intuitive understanding and easier application of the fuzzy rules, ensuring robust decision-making support in recommending NbS to specific workplace conditions.

In the inference engine, the relationships between the input variables—environmental comfort indicators (thermal, acoustic, and lighting) and occupational health indicators (absenteeism, hazardousness, and unhealthiness)—are defined to determine NbS recommendations output (Figure 2).

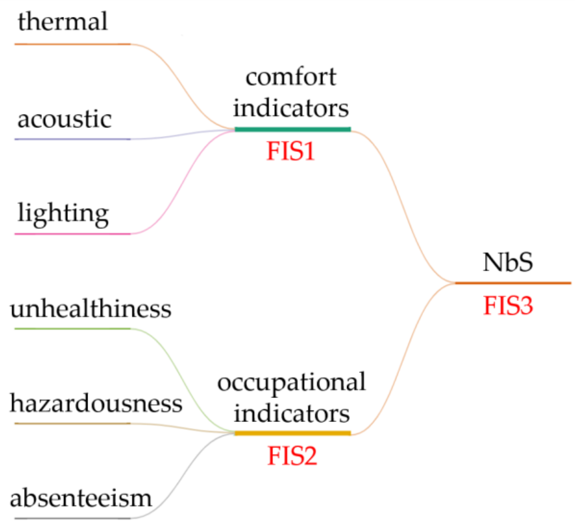

Figure 2. Fuzzy-based DSS for recommending NbS to improve workplace health and wellbeing.

4.4. System Complexity and Integration

To streamline system complexity, two subsystems were devised and integrated. FDSS1 comprises input variables—thermal, acoustic, and lighting comfort—with environmental comfort as the output target. Meanwhile, FDSS2 incorporates input variables—absenteeism, hazardousness, and unhealthiness—addressing occupational health indicators. The rule basis of these preceding systems is introduced in Table 1, which presents the fuzzy rule base for the two inference subsystems—FDSS1 and FDSS2—that assess environmental comfort and occupational health, respectively. These rules define the relationships between the three input variables and the single output variable for each subsystem. The table illustrates the linguistic classifications ('low,' 'medium,' 'high') of input variables and maps their combinations to corresponding output levels ('very low' to 'very high').

FDSS1 evaluates environmental comfort by integrating thermal comfort, acoustical comfort, and lighting comfort. The output reflects the overall environmental comfort level based on these inputs. In turn, FDSS2 assesses occupational health by considering absenteeism, hazardousness, and unhealthiness. Its output represents the occupational health status. Each row in the table specifies a fuzzy rule using a combination of input values, for instance: “If all inputs (e.g., thermal comfort, acoustical comfort, lighting comfort) are 'low,' the output is classified as 'very low.'”

Steps in developing the rule base include:

- Selection of Input Variables: Thermal, acoustical, and lighting comfort were chosen for FDSS1, and absenteeism, hazardousness, and unhealthiness for FDSS2. These were selected based on their prevalence in the literature and their measurable impact on workplace well-being.
- Categorization of Variables: The input variables were

categorized as 'low,' 'medium,' or 'high,' with thresholds defined through expert consultation and literature reviews.

- Fuzzy Logic Operators: Rules were constructed using fuzzy logic operators, enabling the model to handle the inherent uncertainty and gradations in input data.
- Preliminary Testing and Refinement: Simulated scenarios were tested to ensure the rules reflected realistic outcomes. Adjustments were made to optimize the system's responsiveness and accuracy.

Table 1. Rule base for FDSS1 and FDSS2.

input #1	input #2	input #3	output
		low	very low
	low	medium	very low
		high	low
		low	low
low	medium	medium	medium
		high	medium
		low	low
	high	medium	medium
		high	medium
		low	very low
	low	medium	medium
		high	medium
		low	medium
medium	medium	medium	medium
		high	medium
		low	medium
	high	medium	medium
		high	very high
		low	medium
	low	medium	medium
		high	high
		low	medium
high	medium	medium	medium
		high	high
		low	high
	high	medium	very high
		high	very high

Drawing from the two inference systems (FDSS1 and FDSS2), the assembly of the comprehensive inference system (FDSS3) followed, integrating variables from the prior subsystems. This composite system, yielding output values, provides recommendations for NbS in the workplace to enhance occupational health (Table 2).

Table 2. Rule base for FDSS3.

		environmental comfort				
		VL	L	M	H	VH
occupational health	very low (VL)	5	5	4	4	3
	low (L)	5	4	4	3	3
	medium (M)	4	4	3	3	2
	high (H)	4	3	3	2	2
	very high (VH)	3	3	2	2	1

Tables 1 and 2 serve as the foundational structure for our Fuzzy Decision Support Systems. The tables were derived through a systematic process that integrated empirical data and expert judgment. Each rule in the table corresponds to a specific combination of input conditions and their corresponding output, based on the established principles of fuzzy logic. The development of these rules involved several steps:

- Selection of Input Variables: Thermal comfort, acoustic comfort, and lighting comfort were selected based on a review of the literature and their relevance to occupational health and environmental quality indicators.
- Expert Consultation: Domain experts in ergonomics, occupational health, and environmental engineering were consulted to validate the appropriateness of these variables and to help define the rule sets.
- Categorization of Input Variables: The input variables are categorized as 'low', 'medium', or 'high' based on predefined thresholds relevant to workplace health and wellbeing. The outputs are determined by the intersection of these inputs using fuzzy logic operators (AND, OR), which are then mapped to the linguistic output levels ('very low' to 'very high').
- Preliminary Testing: Preliminary versions of the rule base were tested using simulated data to ensure they accurately reflected realistic scenarios. Adjustments were made based on these tests to optimize the decision-making process.

4.5. NbS Recommendations

Table 3 provides a structured framework of recommendations based on the FDSS3 output, which integrates environmental comfort and occupational health indicators. The table categorizes Nature-based Solutions (NbS) into five priority sets, ranging from minimal interventions in optimal conditions to comprehensive actions in extreme scenarios. Each set is designed to address specific workplace conditions and ensure judicious resource allocation.

Table 3. NbS for improving wellbeing in the workplace.

<table>
<tr><th rowspan="2">NbS</th><th colspan="5">recommendations for priority actions based on FDSS3 output</th></tr>
<tr><th>Set 1
in optimal scenarios, solutions for continuous improvement are recommended:</th><th>Set 2
for a high baseline, maintaining and elevating the current standards is paramount:</th><th>Set 3
with moderate levels, there's room for improvement without drastic interventions:</th><th>Set 4
for environments with lower wellbeing indices, more robust measures are necessary:</th><th>Set 5
in extreme scenarios, comprehensive interventions are crucial:</th></tr>
<tr><td>green walls</td><td></td><td></td><td></td><td colspan="2">install vertical gardens to promote a visually appealing workspace and augment air quality</td></tr>
<tr><td>indoor gardens</td><td></td><td></td><td colspan="3">integrate plant arrangements to enhance aesthetic appeal and air quality</td></tr>
<tr><td>natural elements</td><td colspan="5">optimize the use of natural light and introduce natural textures and materials to reinforce the connection with nature</td></tr>
<tr><td>natural light filters</td><td></td><td colspan="4">use adjustable blinds or filters to control and optimize natural light exposure</td></tr>
<tr><td>nature sounds</td><td colspan="5">use soundscapes to mask unpleasant noises and create a calming atmosphere</td></tr>
<tr><td>natural rest zones</td><td></td><td></td><td></td><td></td><td>create comfortable spaces with elements of nature for short breaks</td></tr>
</table>

4.5.1 Key Features of the Recommendation Sets

Set 1. Optimal Scenarios: When workplace conditions are already near optimal, the focus is on continuous improvement through low-cost and non-intrusive interventions. For instance, incorporating subtle natural elements, such as wooden textures or soundscapes (e.g., birdsong or water streams), which enhance the ambiance and mitigate unwanted noise.

Set 2. High Baseline: For workplaces with high well-being indices, the recommendations emphasize maintaining and elevating existing standards. For instance, introducing additional natural light filters or optimizing existing greenery to sustain employee satisfaction while preventing performance decline.

Set 3. Moderate Conditions: In moderately performing workplaces, incremental improvements are suggested to achieve noticeable enhancements without major disruptions. For instance, installing small indoor gardens or vertical green walls to improve air quality and aesthetic appeal.

Set 4. Lower Well-being: For workplaces with significant deficiencies, robust measures are needed to address multiple issues simultaneously. For instance, deploying larger-scale indoor gardens and vertical plant systems to transform air quality and introduce visual relaxation elements.

Set 5. Extreme Scenarios: In the most critical conditions, comprehensive interventions become necessary. These interventions aim to address fundamental deficiencies in environmental and occupational health. For instance, creating natural rest zones equipped with plants, ergonomic furniture, and natural light to provide employees with restorative spaces.

4.5.2 Key Details of Specific Recommendations

- Green Walls: Vertical gardens are highlighted across all sets for their dual role in improving air quality and aesthetics, with the complexity and scale increasing based on workplace conditions.
- Indoor Gardens: Small planters in Set 3 evolve into full-fledged green spaces in Set 5, supporting mental and physical health.
- Natural Elements: Includes wooden finishes, stone textures, or foliage that integrate biophilic principles. These are emphasized in Sets 1 and 2 as cost-effective, scalable options.
- Natural Light Filters: Adjustable blinds or foliage curtains are recommended for all sets to optimize lighting conditions and reduce eye strain.
- Nature Sounds: Audio systems with natural soundscapes, recommended in Sets 1 and 2, enhance focus and reduce stress.
- Natural Rest Zones: Comprehensive in Set 5, these zones serve as dedicated spaces for relaxation and stress recovery, essential in high-stress workplaces.

3.5.3 Rationale and Application

The recommendations in Table 3 prioritize solutions that are:

- Scalable: Start small in optimal scenarios and escalate to significant interventions in challenging conditions.
- Resource-conscious: Encourage efficient use of financial and spatial resources by aligning the level of intervention with workplace needs.
- Holistic: Combine environmental comfort enhancements with occupational health improvements, ensuring balanced well-being outcomes.

5. Case Study

The study was ethically approved by the Human Research Ethics Committee (CAAE 58149622.3.0000.0077). All data collection and analysis adhered to ethical research practices, ensuring confidentiality and informed consent from relevant stakeholders. Data for this study were collected between October and November of 2024, through direct measurements and assessments conducted at the TIP workplace. The data were analyzed following the procedures outlined in the fuzzy logic framework, including parameter setting and validation steps.

5.1. Practical Application

For the practical application of the proposed FDSS, a case study was conducted in a workplace at the Technological Innovation Park (TIP) in São José dos Campos, Brazil (Figure 3). This park is recognized for its efforts to drive technological entrepreneurship and research, aiming to significantly impact the socio-economic development of the region. According to Souza et al. (2016), TIP plays a pivotal role in fostering research and development activities, supporting various technological sectors, and contributing to the overall growth and innovation of the region.

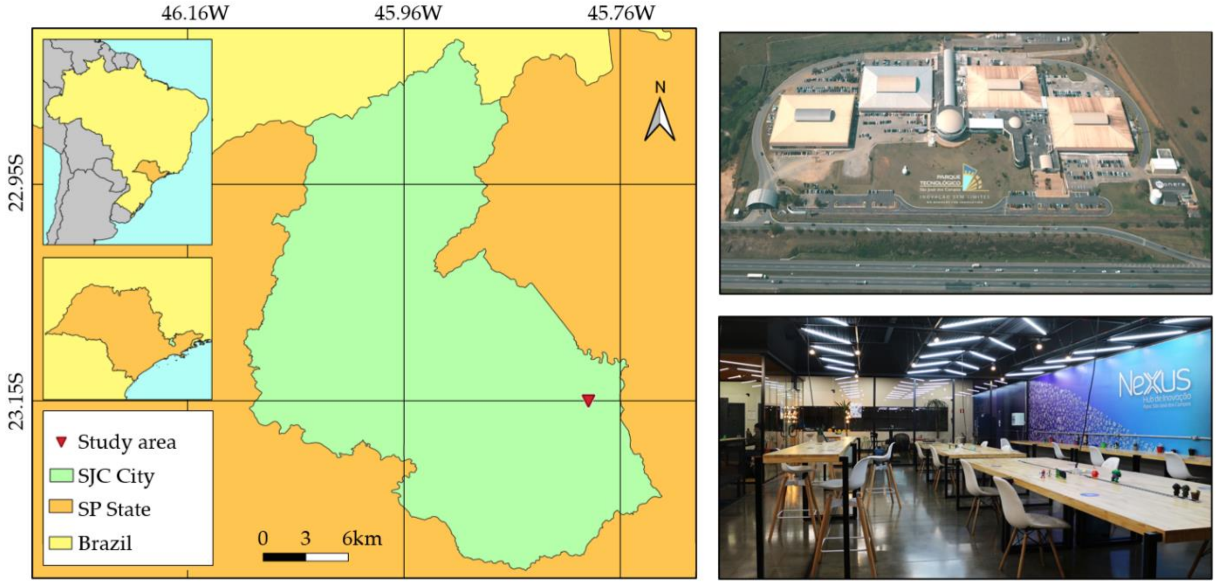

Figure 3. Coworking space, at Technological Innovation Park.

This workplace is dedicated to coworking, shared by approximately 130 startups located in the TIP. Given that coworking spaces need to accommodate a variety of dynamic and collaborative activities, such as project development, meetings, networking, brainstorming, and innovation, the input variables were scored as described in Table 4, for subsequent standardization of the parameters (p).

Table 4. Fuzzy triangle-shaped membership function.

	indicator condition	reference score	parameters (a, b, c)*
thermal comfort (considering degrees Celsius)	low medium high	25-27 23-25 21-23	(24, 26, 26) (22, 24, 26) (22, 22, 24)
acoustical comfort (considering decibels - dB)	low medium high	40-45 35-40 30-35	(43, 43, 37) (32, 37, 43) (37, 32, 32)
lighting comfort (considering lux)	low medium high	300-500 500-800 800-1000	(400, 400, 650) (400, 650, 900) (650, 900, 900)
absenteeism (considering %)	low medium high	2-3 3-5 5-8	(2.5, 2.5, 4) (2.5, 4, 6.5) (4, 6.5, 6.5)
hazardousness (considering factors like air quality, chemical exposure, etc.)	low medium high	1-2/10 3-5/10 6-8/10	(1.5, 1.5, 4) (1.5, 4, 7) (4, 7, 7)
unhealthiness (considering factors like microbial contamination, ventilation, etc.)	low medium high	1-2/10 3-5/10 6-8/10	(1.5, 1.5, 4) (1.5, 4, 7) (4, 7, 7)

* parameters $'a'$ and $'c'$ locate the base and the $'b'$ locates the peak of the triangle-shaped membership function.

Table 4 lists the conditions, reference scores, and parameters (a, b, c) for each indicator, providing a comprehensive view of how each variable is treated within the fuzzy decision support system. The derivation of the reference scores was based on the following steps:

- Literature Reviews: Used to determine typical ranges for each indicator within workplace environments. This data provided a basis for establishing the low, medium, and high thresholds.
- Expert Consultation: Domain experts in workplace ergonomics and environmental health were consulted to refine these ranges based on practical experiences and current standards in occupational health. These experts included:
  a. Ergonomists with extensive experience in workplace design, specializing in optimizing environmental conditions for employee well-being and productivity. Their expertise

ensured that the selected variables and thresholds align with ergonomic best practices and current research findings.

b. Occupational Health Specialists who provided insights into health-related workplace risks, such as exposure to hazardous conditions, absenteeism trends, and factors influencing unhealthiness. Their contributions ensured that the occupational indicators were grounded in empirical health data.

c. Environmental Engineers with a focus on indoor environmental quality. Their input ensured accurate assessments of variables such as thermal comfort, lighting, and acoustical quality, reflecting both industry standards and practical implementation feasibility.

- Statistical Analysis: For each indicator, statistical methods were applied to calculate central tendency measures (mean, median) and dispersion (standard deviation) to define the optimal ranges that best represent typical workplace conditions.
- Parameter Setting: Parameters for each membership function were then set. Here, a and c represent the endpoints of the triangle base, while b defines the peak, corresponding to the most typical or central value of the range. Each score thus reflects a consensus derived from empirical data and expert judgment, ensuring that the recommendations are both scientifically grounded and practically relevant.

The coworking office underwent a thorough assessment, revealing potential discomfort in thermal comfort, indicated by a temperature of 25 degrees Celsius. Acoustical comfort, measured at 53 decibels (dB), suggests a noisy environment, while lighting comfort, at 700 lux, falls below the optimal range. On the occupational health front, absenteeism is at 3%, with hazardousness and unhealthiness rated low at 0 on a scale of 1-10 each. In light of these conditions, the proposed FDSS recommends the implementation of NbS from Set 4, including:

- Green walls and indoor gardens are recommended to address potential discomfort in thermal comfort, introducing natural elements that not only improve air quality but also provide aesthetic benefits, enhancing the overall work environment (Campoverde et al., 2023).
- The integration of natural elements, such as wood and plants, serves to add a biophilic touch, fostering a stronger connection to nature and positively impacting the mood and satisfaction of office occupants (Esmebasi and Lau, 2023).
- For the acoustic challenge, implementing nature sounds, like birdsong or flowing water, becomes crucial to mitigate ambient noise, promoting relaxation and concentration (Xiang et al. 2023).
- To counter the lighting discomfort, the strategic use of natural light filters, diffusing sunlight, is recommended. This not only creates a softer lighting environment but also reduces eye strain, enhancing visual comfort.

Through targeted approach in implementing NbS, the coworking office can effectively address its challenges, resulting in a healthier and more enjoyable workplace for its occupants.

5.2. Strengths and Weaknesses of the FDSS

This brief case study demonstrates that the FDSS was capable of providing a comprehensive assessment of both environmental and occupational health conditions. Its distinctive feature lies in its unique ability to seamlessly integrate variables of diverse nature, addressing the spectrum from environmental comfort to occupational health aspects within the workplace.

One notable strength of the fuzzy system is its adeptness at handling the inherent uncertainty present in the evaluation process. However, the findings of this study are specific to the assessed case, and broader generalizations about fuzzy logic's adaptability across diverse contexts require further validation. Unlike conventional systems, fuzzy logic acknowledges and incorporates ambiguity and subjectivity inherent in comfort limits, which can significantly vary from person to person. In the context of this case study, this flexibility was demonstrated to be particularly useful for addressing the subjective nature of assessments related to well-being and occupational health, offering an improved representation of individual perceptions.

Studies such as Tsiutsiura et al. (2021) corroborate the effectiveness of fuzzy systems in assessing comfort in environments with variable subjective elements, specifically in apartment buildings. Additionally, Menyhárt and Kalmár (2019) developed a new comfort index using fuzzy logic based on subjective responses, further validating the role of fuzzy systems in managing uncertainty within the domain of thermal comfort. Furthermore, the fuzzy logic system excels in integrating distinct nature-related variables, contributing to a more comprehensive understanding of workplace conditions. Nevertheless, the ability of this integration to provide actionable insights for other workplace settings remains dependent on additional research and expanded validation.

This integration is pivotal in capturing the interconnectedness of environmental and health factors, offering a perspective crucial for decision-making in complex scenarios. Within the context of this study, the FDSS demonstrated its capacity to address uncertainty, incorporate subjective comfort limits, and integrate diverse variables. However, these findings are specific to the assessed environment and should not be interpreted as universally applicable without further validation in diverse workplace scenarios.

On the other hand, it is important to critically consider some weaknesses of the FDSS. The accuracy and effectiveness of the FDSS are heavily dependent on the quality and comprehensiveness of the input data. In scenarios where data on environmental conditions or occupational health indicators are incomplete, outdated, or inaccurate, the recommendations generated by the system may be suboptimal or misleading. This reliance on high-quality data poses a challenge in real-world applications where such data might not always be available or easily obtainable.

The FDSS incorporates subjective measures such as perceived thermal comfort, acoustic comfort, and lighting comfort. These variables can vary significantly among individuals, leading to inconsistencies in the data. While fuzzy logic helps manage some of this variability, the subjective nature of these inputs can still introduce a level of uncertainty that affects the reliability of the system's outputs.

The fuzzy logic approach, while powerful, can be complex and difficult to interpret for non-experts. The rules and membership functions involved in the system are not always intuitive, which can make it challenging for stakeholders to understand how the system arrives at specific recommendations. This complexity may hinder the adoption and trust in the FDSS among decision-makers who are not familiar with fuzzy logic principles.

The FDSS framework is designed to handle a specific set of input variables and conditions. Scaling this system to accommodate a wider range of environmental and occupational health indicators or to different types of workplaces may require significant modifications. The fixed nature of the current membership functions and rule sets limits the system's flexibility and adaptability to diverse and evolving workplace environments.

Integrating the FDSS into existing workplace management systems and processes can be challenging. The framework requires seamless integration with other data management and decision-support tools to function effectively. This integration often involves technical and organizational challenges, including data interoperability issues and the need for substantial IT infrastructure investments.

The practical application of the FDSS relies on rigorous validation and calibration against real-world scenarios. While the case study presented in the paper demonstrates its potential, broader validation across various workplace settings is necessary to ensure its robustness and generalizability. Continuous calibration of the system is required to maintain its accuracy over time, considering changing workplace dynamics and environmental conditions.

Implementing the recommended NbS based on the FDSS output can be resource-intensive. Solutions such as green walls, indoor gardens, and natural light filters may require significant financial and logistical resources, which might not be feasible for all organizations. The system does not currently account for the cost-benefit analysis of these interventions, which is crucial for practical decision-making.

In sum, while the FDSS offers a novel approach to enhancing workplace health and wellbeing through biophilic design principles and fuzzy logic, it is imperative to address these weaknesses to enhance its practical applicability and effectiveness. Future research should focus on improving data integration, enhancing user-friendliness, expanding validation efforts, and incorporating cost-benefit analyses to provide a more comprehensive and adaptable decision-support tool.

5.3. Limitations and Future Research

This study, while innovative in applying a fuzzy inference system to recommend NbS for workplace health and wellbeing, has several limitations previously described as weaknesses of the FDSS, which includes data dependency and quality, subjectivity in input variables; scalability and adaptability; and limited validation.

To address these limitations and enhance the robustness, adaptability, and practical impact of the FDSS, establishing it as a valuable tool for promoting workplace health and wellbeing, future research should focus on the following areas:

- Improving Data Collection and Integration: Develop methods for real-time data collection and ensure seamless integration with the FDSS. The use of IoT sensors and big data technologies can improve the quality and accuracy of input data.
- Developing User-Friendly Interfaces: Create intuitive interfaces for the FDSS that facilitate understanding and use by decision-makers without technical expertise in fuzzy logic. Data visualization tools can assist in interpreting system results and recommendations.
- Validating Across Diverse Scenarios: Expand the validation of the FDSS in different types of workplaces and geographic locations. Additional case studies are required to calibrate the system and ensure its general applicability.
- Incorporating Cost-Benefit Analysis: Integrate cost-benefit analysis into the FDSS recommendations to ensure that NbS interventions are economically viable and provide a suitable return on investment.
- Exploring New Indicators: Expand the set of input variables to include other relevant occupational and environmental health indicators, such as air quality and humidity levels, to provide more comprehensive and precise recommendations.
- Conducting Longitudinal Studies: Undertake longitudinal studies to evaluate the long-term impacts of the NbS interventions recommended by the FDSS on employee wellbeing and organizational productivity. These studies will provide a deeper understanding of the sustained effectiveness of NbS.
- Personalizing Recommendations: Investigate methods to further personalize the FDSS recommendations, considering individual employee preferences and the specificities of different sectors and types of work.

Moreover, the exclusion of psychosocial indicators, labor conditions, and additional environmental variables such as ventilation and moisture was intentional due to the scope of the study and data availability. However, we recognize the importance of these factors in shaping workplace well-being. Future research should explore integrating these variables into the model to provide a more comprehensive framework. Expanding the fuzzy system to include subjective indicators like job satisfaction, workload, and organizational culture may offer deeper insights into the interplay between environmental and psychosocial factors, ultimately improving the relevance and applicability of NbS in diverse workplace contexts. In addition, we acknowledge that the current study is limited to a single context, and future research should focus on validating the FDSS across diverse workplace environments. By applying the framework to varied organizational settings, researchers can identify its strengths and weaknesses more comprehensively, enabling continuous improvements. The current proposal serves as a foundational step for ongoing and future enhancements to ensure broader applicability and robustness.

6. Conclusion

The study aimed to make a groundbreaking contribution to the field of workplace health and wellbeing through NbS. By addressing a critical gap that has hindered evidence-based decision-making processes, this research seeks to enhance intervention strategies and inform policy development. However, the findings and contributions of this study are specific to the tested case, and generalizations must be approached with caution.

The proposed FDSS acknowledges uncertainty and integrates diverse variables for a comprehensive understanding of specific conditions. This integration not only optimizes operational efficacy but also contributes to the scientific discourse by highlighting the robustness of fuzzy logic in real-world applications. The FDSS provides a flexible and powerful tool capable of optimizing resource allocation in response to workplace conditions. Recommendations span from simple interventions to complex actions, ensuring judicious use of resources in enhancing occupational health and environmental comfort.

The successful application of the FDSS in a real-world case study demonstrated significant capability to support improvements in workplace conditions. Nevertheless, these results are limited to this context and require further validation across a broader range of scenarios to ensure their applicability, these results are limited to this context and require further validation across a broader range of scenarios to ensure their applicability. The framework's flexibility allows for scalable and adaptable solutions across diverse workplace settings, showcasing its potential for broad applicability. As a limitation, the FDSS relies heavily on data quality and accuracy, which can be influenced by subjective input variables. The system's scalability and adaptability to different workplaces and environments are areas requiring further research. Additionally, while the case study provided promising results, broader validation across various settings is necessary to ensure the system's robustness and generalizability.

Future research should focus on improving data collection and integration, developing user-friendly interfaces, validating the FDSS across diverse scenarios, incorporating cost-benefit analyses, exploring new indicators, conducting longitudinal studies, and personalizing recommendations. These steps will enhance the system's accuracy, effectiveness, and practical impact, establishing it as a valuable tool for promoting workplace health and wellbeing.

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5 MINUTA DE ARTIGO

Nature-Based Solutions for Occupational Environments: A Pathway to Integrated Health, Quality, and Environmental Management

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Abstract: Nature-Based Solutions (NbS) represent a promising interdisciplinary framework to enhance occupational environments by integrating ecological principles into workplace design. Despite extensive evidence supporting the benefits of NbS in public and residential settings, their application in occupational contexts remains underexplored. This study conducts a systematic literature review to evaluate the health, productivity, and environmental outcomes of NbS in workplace environments. Findings highlight that incorporating biophilic elements, such as greenery and natural light, improves employee well-being, cognitive function, and air quality, while reducing stress and absenteeism. However, the study identifies significant barriers to NbS adoption, including cost, lack of expertise, and integration into existing Quality, Environmental, Health, and Safety (QEHS) frameworks. By addressing these challenges, this research aims to advance practical strategies for implementing NbS, fostering sustainable and health-promoting workplaces. The results underscore the dual benefit of enhancing human and environmental health, aligning workplace practices with broader sustainability goals.

Keywords: Nature-Based Solutions; Occupational Health; Workplace Design; Sustainability; Biophilic Design; Environmental Quality; Quality, Environmental, Health, and Safety.

1. Introduction

Nature-Based Solutions (NbS) have increasingly been recognized as an innovative and sustainable approach to address complex environmental, social, and economic challenges (Gillis, 2015; Ling, 2021). Rooted in ecological principles, NbS integrate natural processes and materials—such as vegetation, natural lighting, and organic components—into built environments, promoting biodiversity, resilience, and human well-being (Ling, 2021). *While their transformative potential in urban design and ecosystem restoration is well-documented, their application in occupational settings remains limited*, despite growing evidence of their benefits for human health, productivity, and environmental quality (Petrova et al., 2022).

The exclusion of nature from workplace environments, as highlighted by Gillis (2015), often compromises occupant health and well-being. Integrating natural elements, such as internal gardens and sustainable materials, creates healthier environments, fostering comfort and well-being. Recent studies reinforce that biophilic design enhances psychological resilience, reduces stress, and improves cognitive function (Hutson and Hutson, 2023; Ríos-Rodríguez and Testa Moreno, 2023; Gritzka et al., 2020). Notably, Bratman et al. (2019) demonstrated that nature exposure can reduce cortisol levels, alleviate stress and improve mood.

This is particularly relevant given the increasing complexity of occupational environments, where poor air quality, noise, and inadequate lighting persist as common stressors (Sadick & Kamardeen, 2020). Vasiliev et al. (2022) emphasize that the integration of NbS into Quality, Environmental, Health, and Safety (QEHS) management systems can enhance worker well-being, lower absenteeism, and elevate productivity. Furthermore, Alaghbari (2023) reinforces that sustainable workplace environments balance safety, productivity, and environmental responsibility, fostering resilience.

Despite these promising findings, empirical research specifically addressing NbS in occupational contexts remains scarce (Petrova et al., 2022). The existing literature predominantly focuses on public and residential spaces, underutilizing the transformative potential of NbS in workplaces (Schröter et al., 2022; Collier and Bourke, 2022). A growing body of evidence, however, supports the integration of biophilic principles to address critical workplace challenges—such as enhancing air quality, thermal comfort, and psychological health (Latini et al., 2024).

From a scientific perspective, studying NbS in occupational settings addresses a critical knowledge gap. Given that adults spend the majority of their waking hours at work, leveraging NbS could significantly improve well-being and organizational efficiency (Zhong et al., 2022; Hutson and Hutson, 2023). Petrova et al. (2022) also note that NbS can economically enhance environmental quality and ecosystem services, providing sustainable, long-term strategies that improve employee life quality.

For society and industry alike, implementing NbS offers dual advantages: improving employee health while advancing sustainability goals. Green workplaces not only enhance well-being and reduce absenteeism but also align with corporate social responsibility and sustainability targets (Charisi et al., 2025). As

Collier and Bourke (2022) argue, integrating these solutions from design through to ongoing management ensures sustainable, health-promoting occupational environments.

This research aims to bridge the current gaps by establishing a comprehensive framework for NbS integration into QEHS strategies. By evaluating the dynamic interaction between natural elements and workplace dynamics, it seeks to deliver actionable insights that can inform practice, influence policy, and support healthier, more sustainable, and productive work environments (Yin, 2019). To guide this objective, the study seeks to answer the following research questions: (1) What are the empirical impacts of Nature-Based Solutions on occupational environments in terms of health, productivity, and environmental quality? (2) What are the key barriers and facilitators influencing the successful implementation of NbS within QEHS frameworks?

To ensure rigor and transparency, this study employs a systematic literature review (SLR), structured according to the PRISMA guidelines. This approach will consolidate and critically assess existing evidence on NbS applications in occupational environments, thereby advancing both theoretical understanding and practical implementation frameworks (Zhong et al., 2022).

2. Background

These solutions are grounded in ecological principles, emphasizing co-benefits for humans and the environment. Fundamentally, NbS are characterized by their focus on sustainability, aiming to ensure long-term ecological resilience while minimizing environmental degradation (Katyal, 2024). They simultaneously deliver co-benefits, generating positive outcomes for both human well-being and biodiversity (Delgado-Lemus and Moreno-Calles, 2022). Furthermore, they exhibit adaptability, enabling interventions to be tailored to specific local contexts and to remain flexible under changing environmental and social conditions (Spencer et al., 2024). Ecosystem-based management is also central, advocating holistic approaches that sustain ecosystem services over time (Telesetsky, 2020). Finally, inclusivity is paramount, requiring the engagement of stakeholders across sectors to co-design and effectively implement solutions (Au et al., 2023).

NbS have been successfully implemented across a wide range of sectors, demonstrating notable versatility and effectiveness. Green roofs and walls, for example, play a significant role in mitigating urban heat islands, improving air quality, and promoting mental health by introducing natural elements into dense urban environments (Katyal, 2024; Enu et al., 2022). Urban wetlands, as implemented in cities like Singapore and Melbourne, offer efficient stormwater management, reduce flood risks, and enhance recreational spaces for urban residents (Barman et al., 2024). In the agricultural context, agroforestry systems that integrate trees into farming landscapes have been shown to boost biodiversity, improve soil health, and enhance carbon sequestration capacity (Delgado-Lemus and Moreno-Calles, 2022; Ozment et al., 2021). Similarly, riparian buffers composed of vegetation along waterways effectively reduce nutrient runoff and protect aquatic ecosystems from degradation (Barman et al., 2024).

Coastal areas have benefited extensively from mangrove restoration projects, particularly in Southeast Asia, where these ecosystems function as natural barriers against storm surges while providing crucial habitats for marine biodiversity (Ozment et al., 2021). Coral reef restoration initiatives in the Caribbean and Pacific regions have demonstrated the potential to support local fisheries, promote tourism, and strengthen coastal defenses (Telesetsky, 2020; Nehren et al., 2023). Urban communities have also advanced the establishment of community forests and parks, which expand access to green spaces, encourage physical activity, reduce stress, and improve air quality, thus contributing to healthier urban living environments (Katyal, 2024; Au et al., 2023).

The adaptability of NbS to diverse environmental, social, and economic contexts underscores their transformative potential. However, their application in occupational environments remains largely underutilized, representing a promising frontier for innovation and sustainability in workplace design and management (Enu et al., 2022).

2.2 Occupational Environments and Challenges

Occupational environments significantly influence workers' physical health, mental well-being, and overall productivity. Poorly designed workplaces often expose employees to stressors such as inadequate lighting, poor air quality, excessive noise, and thermal discomfort. These environmental factors are closely linked to adverse health outcomes, including elevated stress, fatigue, and respiratory illnesses, ultimately undermining workplace productivity (Bressane and Castro, 2025).

Emerging research highlights the critical relationship between workplace environments and employee performance. For instance, natural light has been shown to regulate circadian rhythms, thereby improving sleep patterns and cognitive performance (Callaghan, 2015). Additionally, the integration of greenery within workspaces significantly reduces stress and enhances creativity and cognitive function (Hutson and Hutson, 2023; Charisi et al., 2025).

Despite these documented benefits, many workplaces, particularly in urban and industrial settings, continue to prioritize operational efficiency over occupant well-being, frequently neglecting opportunities to enhance environmental quality (Langer, 2021). Compounding this issue, the global rise in sedentary work patterns has been directly associated with heightened risks of physical inactivity, musculoskeletal disorders, and mental health challenges (Klen, 2021).

In response to these multifaceted challenges, organizations have adopted a variety of strategies aimed at fostering healthier and more sustainable occupational environments. Biophilic design, for instance, involves the deliberate incorporation of natural elements such as plants, water features, and organic materials into architectural spaces, a practice shown to improve emotional well-being, stimulate creativity, and reduce absenteeism (Morsy Mohamed, 2021; Roskams, 2021). Efforts to enhance indoor air quality through advanced HVAC systems have also been pursued, although these technological solutions often fail to capture the full ecosystemic benefits offered by NbS, which can simultaneously purify air and elevate psychological comfort (Zhong et al., 2022).

Moreover, the adoption of green certification frameworks, such as LEED and WELL, has encouraged more sustainable building practices and healthier indoor environments. Nonetheless, these certifications frequently fall short in integrating the multifunctional potential of NbS into their criteria (Augustin and Oseland, 2025). Mental health programs, including mindfulness training and flexible work arrangements, have become increasingly prevalent. However, such initiatives tend to underexploit the restorative advantages of nature-connected spaces (Charisi et al., 2025).

Despite growing awareness of these strategies, organizations continue to face significant barriers, notably cost constraints, limited knowledge, and insufficient access to specialized expertise. These limitations underscore the considerable untapped potential of NbS as scalable and integrative solutions capable of concurrently enhancing occupational health, productivity, and environmental quality (Bressane and Castro, 2025).

2.3 Existing Evidence on NbS Benefits

Although there is substantial evidence supporting the benefits of NbS in non-occupational contexts, their integration into workplace environments remains insufficiently explored. This oversight is particularly notable, given that many of the challenges NbS effectively address—such as inadequate air quality, thermal discomfort, and psychological strain—are also prevalent in work settings (Zhong et al., 2022). Preliminary studies, however, suggest that NbS could be transformative for occupational health and organizational performance.

In terms of physical health, the integration of greenery and natural light within office spaces has been associated with reductions in respiratory issues and improvements in sleep quality, both of which contribute to overall physical well-being (Callaghan, 2015; Hutson and Hutson, 2023). Regarding mental well-being, exposure to natural elements in the workplace significantly reduces anxiety and boosts employee morale, leading to decreased absenteeism and higher retention rates, mirroring results observed in residential environments (Charisi et al., 2025; Roskams, 2021). Environmental quality also benefits from the adoption of NbS, as the incorporation of indoor green walls and natural ventilation systems enhances air circulation and attenuates ambient noise levels, thereby creating more comfortable and cognitively supportive workspaces (Morsy Mohamed, 2021; Zhong et al., 2022). Furthermore, at the organizational level, NbS have demonstrated the capacity to improve environmental conditions and increase employee satisfaction, resulting in heightened productivity and reduced operational costs related to health issues and absenteeism (Charisi et al., 2025; Augustin and Oseland, 2025).

While these preliminary findings are promising, there remains a clear gap in systematic research regarding the implementation and outcomes of NbS in occupational settings. Addressing this gap is essential to establish empirical foundations and develop practical frameworks that enable organizations to successfully integrate NbS into workplace design and management practices.

3. Methodology

This research employed a SLR to examine the multifaceted benefits associated with the implementation of NbS, with particular emphasis on occupational health, psychological well-being, organizational productivity, and environmental sustainability.

3.1 Systematic Review Framework

The SLR followed the PRISMA guidelines, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Liberati et al., 2009). The Scopus database was preferred for this research due to its multidisciplinary coverage and large number of records combining search terms such as 'Nature-Based Solutions' and 'Nature Exposure' using the following Boolean operators (Table 1).

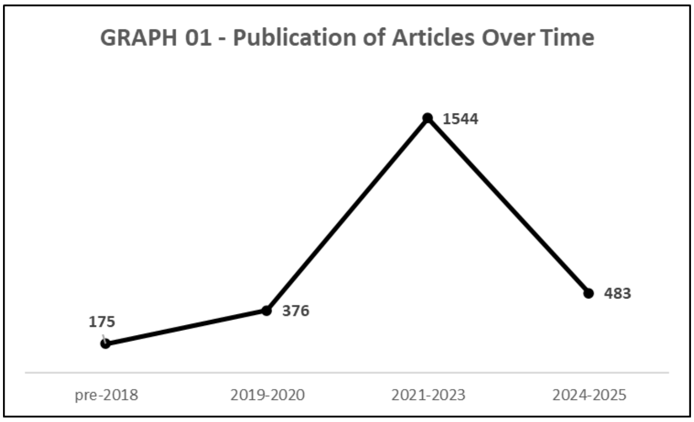
Table 1. Database Search Strategy.

Category	Term / Combination	Operator
Nature	"Nature-based solutions", "Biophilic Design", "Nature Exposure"	OR
Results	"Sustainability", "Health", "Stress", "Productivity", "Occupational Health and Safety", "Quality and Management"	OR
Tools	"Nature-based solutions", "Fuzzy"	OR
Filters	2019-2024, Impact Factor > 1, Search in: Article Title, Abstract, Keywords	AND

By utilizing a strategic combination of keywords applied to article titles published between 2019 and 2024, the initial search yielded 2,578 records, of which 159 were preliminarily selected for further evaluation. Following the removal of duplicate entries, 146 unique studies remained (Table 2). Eligibility criteria included publication in peer-reviewed journals with an impact factor exceeding 4, as well as relevance verification through a targeted assessment of titles to ascertain alignment with the study's research questions.

Table 2. Search strategy.

Term / Combination	Total - Search 2019 - 2024	Total Retained
"Nature-based solutions" AND Sustainability	815	44
"Nature-based solutions" AND Health	616	29
"Nature-based solutions" AND Quality AND Management	406	3
"Nature-based solutions" AND Stress	242	6
"Nature-based solutions" AND Productivity	127	12
"Biophilic Design" AND Productivity	52	16
"Nature Exposure" AND Health	194	37
Fuzzy AND "Nature-based solutions"	19	6
Fuzzy AND "Occupational Health and Safety"	107	6
Total	**2578**	**159**
Total after duplicate removal		**146**



According to Graph 01, scientific output on nature-based solutions shows explosive growth, particularly since 2021. While publications before 2018 and between 2019-2020 totaled 115 and 316 records respectively, the 2021-2023 period saw a peak of 1,544 publications. This phase accounts for approximately 64% of the total publications cataloged up to 2025, signaling strong consolidation and accelerated maturation of the field. The substantial recent volume highlights the growing prominence of these solutions in academic research.

Subsequently, these studies were systematically classified into nine thematic categories to facilitate a structured screening of their titles and abstracts for relevance and methodological rigor. Thereafter, the titles and abstracts of the shortlisted articles were meticulously screened to evaluate their relevance against predefined inclusion criteria. The selection parameters prioritized studies that examined the benefits of NBS across diverse operational contexts and occupational settings, while also incorporating a robust theoretical foundation. This resulted in 86 articles being retained, with the reasons for exclusion shown in Table 3.

Table 3. Retained and reasons of exclusion.

Category	Qty.	Retained	Reasons of exclusion
NBS Benefits	43	30	Focused on non-occupational contexts (e.g., public parks, residential areas). Lacked quantitative health/productivity metrics (e.g., stress reduction without cortisol data). Addressed mental health outcomes without workplace-specific interventions. Superficially mentioned NbS without empirical validation (e.g., anecdotal claims).
Certifications	1	1	N/A
HxN Connection	1	1	N/A
Education	3	2	Examined academic performance (e.g., student productivity) without workplace relevance.
Fuzzy	7	6	Applied fuzzy logic to unrelated domains (e.g., supply chain risk) without NbS linkage.
Occupational	16	16	N/A
Urban Planning	47	13	Prioritized city-scale infrastructure (e.g., green corridors) over workplace design. Focused on policy/governance without practical implementation in occupational settings. Addressed flood/stormwater management without health or productivity co-benefits.
Review	20	10	Broadly discussed NbS without occupational health or QEHS alignment. Synthesized evidence on ecosystem services (e.g., carbon sequestration) unrelated to workplaces. Lacked critical appraisal of NbS implementation barriers in corporate settings.
VR	8	7	Lacked protocols for translating VR nature exposure into workplace design guidelines.
TOTAL	**146**	**86**	

Following this preliminary screening, the articles underwent a critical appraisal using the Joanna Briggs Institute (JBI) Checklist to ensure methodological rigor, reliability, and validity of the findings (Barker, 2024).During the screening process, studies were retained based on their alignment with the following guiding question: "Does the article examine or substantiate the application of NBS in the integrated management of quality, environmental sustainability, occupational health, and workplace hygiene? Furthermore, does it employ a theoretical framework and fuzzy logic methodology to develop decision-support systems pertinent to NbS?" This rigorous selection process yielded 86 articles for full-text review. After applying the JBI critical appraisal criteria, an additional six articles were excluded, resulting in a final cohort of 80 studies underpinning the systematic review. The following tables illustrate the approach taken and considerations regarding the applied JBL methodology (Tables 4 to 8).

Table 4. General distribution of articles.

Category	Quantity	Percentage	Details
Total Articles Analyzed	86	100%	Complete database.
Excluded Articles	6	7%	Reasons detailed in Table 3.
Included Articles	80	93%	Evaluated per JBI criteria.

Table 5. Predominant methodologies in 80 included articles.

Methodology	Quantity	Percentage	Application Example
Systematic Reviews	20	25%	Synthesis of evidence on NBS and mental health.
Experimental Studies	15	18%	VR or biophilia interventions.
Observational Studies	18	22%	Longitudinal data (e.g., cortisol levels).
Qualitative Studies	10	12%	Interviews on green space perceptions.
Data Modeling/Analysis	19	23%	Fuzzy logic, bibliometrics, or machine learning.
Total	**80**	**100%**	

Table 6. Reasons for excluding 6 articles.

Reason	Quantity	Percentage	Example
Lack of Methodological Clarity	2	33%	Undescribed methods.
Unrepresentative Sample	1	17%	15 participants, no demographic diversity.
Confounding Bias	1	17%	No control for socioeconomic factors.
Non-Significant Results	1	17%	Insignificant differences in ROS scale.
Off-Topic	1	16%	Building certifications unrelated to health.
Total	**6**	**100%**	

Table 7. Justification for Including "borderline" articles.

Inclusion Criterion	%	Contribution
Policy Relevance	30	Supports green infrastructure policies.
Methodological Innovation	25	New tools for psychological assessment.
Emerging Evidence	20	Solutions for polluted urban environments.
Understudied Contexts	15	Highlights nature-access inequalities.
Interdisciplinary Value	10	Integrates architecture and occupational psychology.
Total	**100**	

Table 8. Rigor vs. relevance summary.

Category	%	Details
JBI-Compliant Articles	88	Followed strict methodological criteria.
Justified "Borderline" Articles	12	Included for unique contributions (e.g., innovation or critical context).

Of these, 51 articles provided substantive empirical data suitable for inclusion in the final synthesis. The PRISMA flow diagram (Figure 1) visually illustrates the systematic progression of records through identification, screening, eligibility, and inclusion stages for qualitative synthesis.

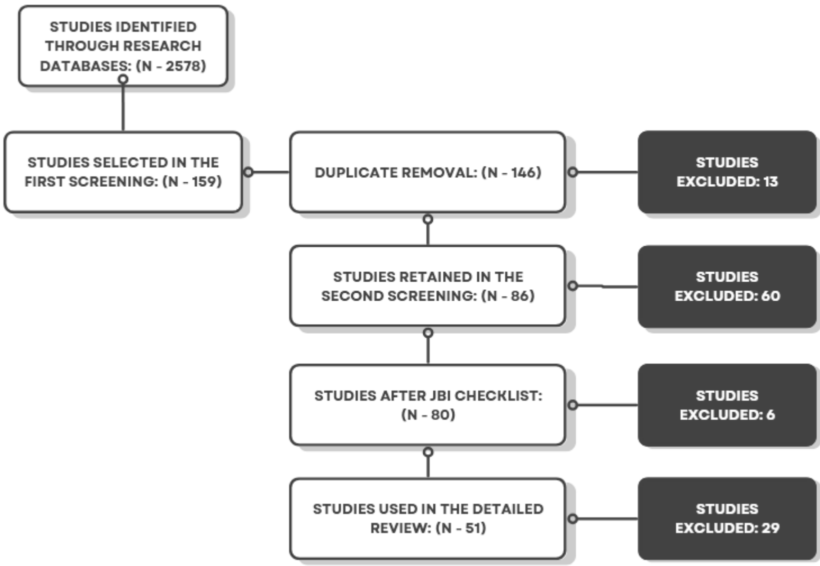


Figure 1. PRISMA flow diagram.

3.1 Findings

The comprehensive analysis of the selected studies revealed the multifaceted impacts of NbS on human health and psychological well-being, as well as their influence on organizational productivity and strategic planning for environmental management. Within these overarching domains, a series of additional subthemes emerged, which are systematically delineated and synthesized in the subsequent tables for clarity and comparative analysis (Tables 9 and 10).

Table 9. Findings - NBS Benefits.

Benefits	Findings	Authors
Health and Well-being	• Stress reduction and respiratory improvement • Cardiovascular improvement (including obesity, blood pressure, and cortisol reduction) • Immune system enhancement • Reduction of physical and mental fatigue • Sleep improvement • Reduction of Sick Building Syndrome • Psychological improvement (including reduced depression symptoms) • Emotional comfort and restoration • Reduction of mental exhaustion • Increased self-esteem and body appreciation • Improved cognitive performance & creativity • Therapeutic benefits • Overall health and well-being improvement	Prodanović et al.; Seddon et al.; Liu et al.; Vitale et al.; Zhang et al.; Al-Dmour et al.; Gritzka et al.; Paredes-Céspedes et al.; White et al.; Wickenberg et al.; Kolokotsa et al.; Chan et al.; Andersen et al.; Martin et al.; Stork et al.; Fukano et al.; Özgenç et al.; Mostajeran et al.; Thapa et al.; Barnes et al.; Coletta et al.; Zhong et al.; Jimenez et al.; Kumpulainen et al.; Ramm et al.; Lei et al.; Khatib et al.; Yu et al.
Financial and/or Productive Return	• Increased property value • Ecosystem savings (water, energy, etc.) • Productivity increase • Reduced turnover • Reduced absenteeism • Improved organizational efficiency • Reduced healthcare costs • Savings compared to gray infrastructure	Prodanović et al.; Seddon et al.; Gritzka et al.; Zhang et al.; Yildirim et al.; Yeo et al.; Mata et al.; Yu et al.; Sadick et al.; Yin et al.; Candido et al.; Zhong et al.; Jimenez et al.; Lei et al.; Ramm et al.; Fastenrath et al.; Sebestyén et al.; Özgenç et al.; Oturakci.
Workforce Retention and Satisfaction	• Job satisfaction and reduced turnover • Greater engagement • Mood improvement • Increased motivation • Higher morale and collaboration	Gritzka et al.; Wallmann-sperlich et al.; Yeo et al.; Yu et al.; Stork et al.; Özgenç et al.; Zhong et al.; Ramm et al.; Lei et al.

Table 10. Findings on planning and management (P&M).

P&M	Findings	Authors
Stakeholder Engagement	• Participatory methodologies and solutions • Public participation • Inclusive management • Institutional process and policy development • Involvement from conception	Liu et al.; Wickenberg et al.; Demirkol et al.; Yu et al.; Pereira et al.; Coletta et al.; Lopes et al.; Ausseil et al.
Type of NBS Intervention	• Rain gardens and green roofs • Integrated vegetation systems in buildings • Green and open spaces • Green corridors • Virtual Reality (Forests and Deserts) • Microalgae for air purification • Gardening and horticulture • Plants in work environments	Al-Dmour et al.; Demirkol et al.; Dick et al.; Yu et al.; Stork et al.; Özgenç et al.; Mostajeran et al.; Yin et al.; Thapa et al.; Aristizabal et al.; Kumpulainen et al.; Lei et al.; Lyu et al.; Pereira et al.
Implementation Challenges	Financial and regulatory barriers (lack of long-term funding, adaptation costs) • Technical and methodological difficulties (lack of standardization, inconsistent metrics, technical complexity) • Structural and operational limitations (dependency on gray infrastructure, space constraints, geographic restrictions) • Certification and validation challenges (unrecognized methodologies, lack of context-specific evidence) • Measurement and evaluation difficulties (subjectivity, challenges in data collection) • Socio-institutional and adaptation barriers (public involvement, resistance to new technologies like VR)	Prodanović et al.; Seddon et al.; Reyes et al.; Yin et al.; Paredes-Céspedes et al.; Wickenberg et al.; Yildirim et al.; Martin et al.; Stork et al.; Özgenç et al.; Sadick et al.; Mostajeran et al.; Yin et al.; Thapa et al.; Coletta et al.; Lopes et al.; Hähn et al.; Ausseil et al.; Oturakci et al.
Long-term Challenges	•Financial and management challenges (continuous funding, adaptive management, lack of organizational/political stability) • Technical and operational limitations (ongoing maintenance, temporal degradation, reliance on qualitative data) • Methodological and evaluation barriers (lifecycle analysis of NBS, lack of dynamic indicators, generalized solutions, selection bias) • Technological adaptation challenges (discomfort with VR, slow evolution of certifications) • Cultural and social barriers (resistance to adopting new solutions)	Prodanović et al.; Seddon et al.; Reyes et al.; Lyu et al.; Pereira et al.; Yildirim et al.; Dick et al.; Yu et al.; Stork et al.; Özgenç et al.; Candido et al.; Coletta et al.; Aristizabal et al.; Hähn et al.; Kumpulainen et al.; Lei et al.

The findings demonstrate substantial and direct implications for occupational environments, emphasizing the relevance of NbS in enhancing workplace health and productivity. While the majority of the reviewed studies primarily focused on urban settings, analogous outcomes were consistently observed in occupational contexts, thereby supporting the validity of cross-contextual, similarity-based analyses. The subsequent sections provide an in-depth examination of the key findings corresponding to the thematic subcategories outlined in Table 5.

4. Results

4.1 Health and Well-being

The relationship between health and well-being in the work environment has become an increasing concern, and the integration of NBS in corporate settings has been redefining this relationship (Gritzka et al., 2020; Vitale et al., 2024). Recent research indicates that exposure to natural elements — such as green spaces, indoor plants, open and well-ventilated environments, and even sounds and images of natural settings — enhances both physical and psychological health (Prodanović et al., 2024; White et al., 2019; Liu et al., 2021).

4.1.1 Mental Health

Prodanović (2024) demonstrated through biomarkers that 30 minutes of exposure to vegetative environments reduces cortisol levels by 15–28%. This aligns with the research by White et al. (2019), which showed a 23% reduction in depressive disorders after 120 weekly minutes of nature exposure. Meanwhile, interventions such as integrating vegetation and natural light into the work environment were proven to reduce employee burnout symptoms by up to 37%, particularly in high-pressure roles and results-driven settings (Gritzka et al., 2020; Al-Dmour et al., 2021).

Further reinforcing the relevance of exposure to natural elements, Paredes-Céspedes et al. (2024) demonstrate in their studies that a simple walk-through tree-filled environments reduces symptoms of anxiety and depression by up to 25%. Even the mere viewing of natural images and landscapes showed an 18% improvement in emotional regulation (Vitale et al., 2024). All of this supports the evolutionary hypothesis of Fukano and Soga (2024), which suggests that humans' preference for green environments is an adaptive mechanism, thus explaining these positive emotional responses.

Similarly, Chan et al. (2023) studied the use of digital interventions, such as Virtual Reality (VR), where a 22% reduction in anxiety was also observed following 20-minute VR sessions with natural scenery. At the same time, the use of VR with both desert and green landscapes was shown to reduce stress (Yin et al., 2022).

4.1.2 Physical Health

Beyond mental health benefits, studies conducted in areas with dense vegetation have reported a 12% reduction in hypertension rates and an 18% decrease in hospitalizations for respiratory diseases, largely due to the pollutant-capturing capacity of plants (Liu et al., 2021; Kolokotsa et al., 2020). Similarly, Andersen et al. (2021) observed strengthened immune responses linked to nature exposure. These findings are consistent with Al Khatib et al. (2024), who demonstrated that hospital patients with access to therapeutic gardens experienced faster recovery and a 22% reduction in analgesic use.

Green spaces also contribute to metabolic health. Kolokotsa et al. (2020) reported a 7% reduction in BMI, while proximity to natural environments has been shown to enhance sleep quality by regulating circadian rhythms (Martin et al., 2024).

4.1.3 Cognition and Productivity

Incorporating biophilic elements into office spaces has proven to enhance cognitive performance, resulting in a 15% increase in productivity and a 30% improvement in cognitive tasks (Lei et al., 2021). Exposure to nature also improved perceived attention by 20% (Nguyen et al., 2024) and fostered a 30% boost in creativity (Ramm et al., 2024). Furthermore, Yin (2019) highlights that VR environments simulating nature can enhance spatial reasoning.

4.2 Financial Returns

NBS have emerged as a strategic investment for organizations. Institutions that integrated natural ecosystems into their facilities reported gains in productivity, alongside reductions in absenteeism, staff turnover, structural costs, and healthcare expenditures (Al Khatib et al., 2024; Candido et al., 2021; Yu et al., 2020). These findings reinforce the compatibility of environmental preservation with profitability, demonstrating that ecological balance and economic success can indeed progress together (Prodanović et al., 2024).

4.2.1 Asset Appreciation and Revenue

According to Prodanović et al. (2024), properties located near gardens and natural landscapes appreciated by up to 6%, reflecting a growing demand for spaces that harmonize aesthetics with functionality. Additionally, certified buildings featuring green roofs and vegetated fades not only enhanced energy efficiency but also increased their market value (Reyes et al., 2024).

4.2.2 Reduced Operational and Healthcare Costs

NBS also present a cost-effective alternative to conventional gray infrastructure. Green roofs and wetlands can lower operational costs by as much as 30% compared to traditional methods (Seddon et al., 2020). In corporate environments, offices incorporating indoor vegetation reported a 15% reduction in climate control expenses, thanks to the thermal insulation properties of plants (Lei et al., 2021).

Another significant advantage is the decline in respiratory and cardiovascular diseases associated with proximity to natural settings. Jimenez et al. (2021) demonstrated that a 10% increase in urban tree cover results in approximately $10 in healthcare savings per resident. Hospitals that installed living walls experienced a 22% reduction in analgesic use, effectively decreasing medication expenditures (Al Khatib et al., 2024).

Moreover, WELL and LEED-certified workplaces reported a 25% decline in absenteeism, largely attributed to lower levels of chronic stress among employees (Candido et al., 2021). Similarly, offices employing VR to simulate natural environments achieved 12% productivity gains through faster task completion (Mostajeran et al., 2021). Complementary to these findings, Yu et al. (2020) observed an 18% reduction in turnover costs from simple interventions such as the inclusion of indoor plants.

4.2.3 Productivity and Talent Retention

In workplace settings, Sadick and Kamardeen (2020) found that nature-integrated offices directly enhance employee efficiency. Natural light and greenery contributed to a 12% increase in productivity, with tasks completed 15% faster without compromising quality. Additionally, exposure to biophilic elements boosted creativity by 18% in VR-based experiments (Ramm et al., 2024).

In another context, incorporating water features and aquariums into workplaces reduced conflict resolution time by 25%, an effect attributed to the calming influence of flowing water sounds (Yildirim et al., 2024). Likewise, living walls in intensive care units (ICUs) contributed to a 9% reduction in medical errors, associated with lower self-reported stress levels (Kolokotsa et al., 2020).

Job satisfaction is a crucial factor for organizations, as it directly affects both talent retention and productivity. Companies certified by LEED and WELL reported a 25% lower turnover rate, driven by employees' enhanced sense of personal value and well-being in natural environments (Candido et al., 2021). In the hospitality sector, workers also experienced reduced stress due to NBS interventions, which resulted in a 30% decrease in absenteeism (Yu et al., 2020).

4.3 Workforce Retention

High turnover imposes multiple challenges on organizations, including process disruptions, weakened corporate culture, and compromised quality and management outcomes. However, exposure to natural elements has proven to be a highly effective strategy for retaining talent (Jimenez et al., 2021; Candido et al., 2021). Companies that invested in open environments, indoor vegetation, and natural lighting reported lower turnover rates and higher employee engagement, fostered by greater emotional balance and stronger organizational loyalty (Candido et al., 2021).

4.3.1 Connection with Nature

Jimenez et al. (2021) reported that simply offering views of parks and gardens within buildings led to a 30% decrease in employees' intention to leave, compared to environments devoid of natural elements. Moreover, the presence of indoor vegetation was linked to a reduction of up to 22% in chronic stress, a crucial factor for retaining employees in high-pressure roles (Hähn et al., 2021).

Biophilic design has also proven effective in creative environments, such as design studios. The integration of organic wood, fractal patterns, and access to green balconies contributed to a 40% reduction in voluntary resignations over a one-year period, as employees reported heightened creativity and reduced feelings of "entrapment" in repetitive tasks (Zhong et al., 2022).

Furthermore, employees in companies with sustainable certifications, such as LEED and WELL, expressed a stronger sense of personal value and greater satisfaction in working for an organization perceived as more ethical. This perception translated into retention rates up to 25% higher than those observed in conventional buildings (Candido et al., 2021).

4.3.2 Mental Health and Belonging

Work environments of all types can benefit from integrating nature. For instance, the introduction of therapeutic gardens and green walls in hospitals led to a 35% reduction in nurse burnout and fewer requests for departmental transfers (Al Khatib et al., 2024). Healthcare professionals with access to nearby green spaces during their breaks reported up to a 20% higher willingness to remain with their organization (Kolokotsa et al., 2020).

According to Mostajeran et al. (2021), even virtual reality interventions can contribute positively to mental recovery. Employees in technology companies who engaged with natural landscape simulations during breaks experienced a 15% reduction in turnover over six months. In the hospitality sector, workplaces featuring indoor gardens and rooms with views of natural settings saw a 30% decline in turnover, an effect linked to increased institutional pride and stronger alignment with company values (Yu et al., 2020).

Beyond individual benefits, NBS foster collective engagement. At a German multinational, teams that collaboratively cultivated an urban garden experienced a 25% reduction in internal conflicts, alongside improved task cohesion and fewer departmental transfer requests (Wickenberg et al., 2022). Similarly, factories with tree-lined break areas reported enhanced relations between management and production staff, leading to an 18% decrease in resignation requests over the course of a year (Oturakci, 2019).

Active involvement in the planning and implementation of NBS also heightened the sense of belonging among employees. In Sydney, staff who participated in developing a green roof for their company reported a 40% increase in satisfaction with their work environment, resulting in turnover being halved over a two-year period (Prodanović et al., 2024).

4.4 Engagement

Exposure to nature within the workplace has proven to be a valuable factor in enhancing employee engagement. Organizations that incorporated natural landscapes, sunlight, and green spaces into their office environments observed increased team focus, along with sustained satisfaction and a stronger sense of connection to institutional goals (Yildirim et al., 2024; Kolokotsa et al., 2020).

Multisensory interventions, such as the use of natural scents like pine and the ambient sound of rain, further elevated engagement levels, delivering up to 35% greater focus during repetitive tasks, as indicated by eye-tracking sensor measurements (Yildirim et al., 2024). Similarly, biophilic design strategies — including integrated vegetation, natural materials, and dynamic lighting — contributed to engagement by promoting directed attention restoration. EEG studies revealed that employees exposed to these natural elements experienced a 15% reduction in cognitive load during complex tasks, resulting in a 12% increase in accuracy (Aristizabal et al., 2021). Moreover, workplaces with natural views recorded an 18% improvement in team collaboration compared to environments lacking such stimuli (Candido et al., 2021).

4.5 Types of NBS

The studies analyzed identified a variety of NBS types, with green infrastructure emerging as the most versatile category. Green roofs and vegetated walls function as thermal and acoustic insulators, helping to reduce ambient temperatures and noise pollution while capturing fine airborne particles (Reyes et al., 2024; Prodanović et al., 2024; Zhong et al., 2022; Pereira et al., 2023). In parallel, parks and ecological corridors promote recreation, lower temperatures, and enhance habitat connectivity (Barron and Rugel, 2023; Thapa et al., 2024).

Built environments incorporating biophilic design offer multiple benefits for occupants. Green façades using mosses, for instance, have been shown to improve cognitive performance due to terpene emissions (Yildirim et al., 2024; Mata et al., 2021). Natural lighting systems help synchronize biological rhythms, fostering restorative effects (Candido et al., 2021). Solar chimneys enable natural ventilation, reducing energy consumption by up to 25% (Wallmann-Sperlich et al., 2019), while aquariums support health recovery (Al Khatib et al., 2024).

Corporate spaces can benefit from vegetated walls, whether hydroponic or substrate-based, enhancing both visual appeal and indoor air quality (Al-Dmour et al., 2021). Low-maintenance and resilient plant species can also be distributed across desks, meeting rooms, and shared areas (Hähn et al., 2021). Zhong et al. (2022) highlights the use of natural materials — such as wood, stone, and fibers — for flooring, partitions, and furniture, introducing organic textures and enriching sensory connection. Demirkol (2024) further discusses the incorporation of forms inspired by nature, such as leaves, shells, and undulating walls and ceilings. Color schemes reflecting natural environments, paired with natural lighting, can also be adopted (Aristizabal et al., 2021). According to Lyu et al. (2022), outdoor or semi-covered rest areas featuring elements like waterfalls or reflecting pools foster relaxation.

Balconies and terraces, equipped with wooden benches and natural plants, serve as informal meeting spaces and restorative break areas (Candido et al., 2021). Yildirim et al. (2024) suggests biophilic transitional corridors, integrating suspended vegetation, indirect lighting, and ambient sounds. The study also notes that nature-inspired sounds — such as rain, streams, birdsong, or forest ambience — can be utilized for meditation or to mask urban noise. Recognizing the importance of human sensory experience, aromatherapy using essential oil diffusers is recommended to enhance focus in high-concentration areas such as training rooms (Lopes et al., 2024). Demirkol (2024) additionally highlights the use of textured flooring that mimics grass, pebbles, or sand in decompression zones.

However, not all environments can accommodate natural elements directly. In such contexts, virtual reality (VR) emerges as an effective and practical alternative. Kumpulainen et al. (2024), in a study involving nurses, reported a 20% reduction in emotional fatigue following five-minute virtual forest sessions. Similarly, call center employees exposed to 360° natural landscape projections experienced a 15% increase in productivity and a 30% reduction in absenteeism (Mostajeran et al., 2021).

Factory workers also reported a 30% decrease in afternoon headaches after VR sessions depicting rivers and forests during lunch breaks (Oturakci, 2019). Furthermore, 20-minute VR sessions showcasing natural scenes were associated with up to a 22% reduction in anxiety (Chan et al., 2023), while environments simulating deserts and greenery helped lower perceived stress (Yin et al., 2022). Ramm et al. (2024) demonstrated that AI-enhanced VR environments can increase engagement by 25%, adjusting scenarios in real time based on physiological responses. Monitors displaying natural landscapes can substitute for urban views (Zhang et al., 2023), while dynamic lighting with warm and cool tones can optimize ambiance throughout the day (Aristizabal et al., 2021).

Hybrid strategies also show promise. Mata et al. (2021) describes indoor fountains with plant-based filtration systems that purify and humidify the air, while Reyes et al. (2024) presents pre-cultivated moss or fern modules that serve dual purposes of acoustic insulation, thermal regulation, and aesthetic enhancement.

4.6 Challenges

Despite the numerous benefits associated with NBS, several challenges merit attention. As highlighted by Özgenç et al. (2024), the effectiveness of NBS varies according to geographic, cultural, and organizational contexts. For instance, arid regions face high installation and maintenance costs for green roofs, reducing interest in these solutions by half. Similarly, organizations with fragile corporate cultures have reported lower engagement in participatory projects, often due to distrust in senior leadership and decentralized decision-making processes (Gritzka et al., 2020).

Another concern is unequal access to NBS. Some environments enjoy higher investment intentions and availability of resources than others, illustrating environmental inequity (Sebestyén et al., 2023). Even though many solutions yield long-term savings, their high upfront costs remain a significant barrier (Stork et al., 2023; Mata et al., 2021). The reliance on self-reported data can also introduce bias (Barnes et al., 2019), while the scarcity of studies examining long-term outcomes — beyond two years — underscores the need for longitudinal research (Coletta et al., 2021).

4.6.1 Costs and Specialized Labor

One of the main obstacles lies in the elevated initial investment required for certain NBS, such as green roofs, rain gardens, and sustainable drainage systems, due to the cost of materials, specialized labor, and necessary structural adaptations (Reyes et al., 2024; Liu et al., 2024). In arid climates, the need for continuous irrigation drives up operational costs, challenging financial viability (Reyes et al., 2024). Additionally, advanced technologies like microalgae-based air purification remain expensive and underutilized (Mata et al., 2021).

Another critical issue is the shortage of qualified professionals capable of designing and managing green infrastructure, which demands specialized knowledge in ecology, engineering, and architecture — skills still scarce in the market (Coletta et al., 2021). A lack of familiarity with water and structural efficiency management further complicates project implementation (Reyes et al., 2024).

While green roofs typically require about 20% higher upfront investment than conventional alternatives, their lifespan of over 25 years and energy savings of up to 30% help to balance costs in the medium term (Mata et al., 2021). Participatory initiatives, such as community gardens, also depend on continuous funding and sustained engagement from participants (Sebestyén et al., 2023).

4.6.2 Resistance

Culturally, there remains a preference for traditional "gray" infrastructure, such as concrete and steel. For example, São Paulo's conventional drainage system delayed the adoption of NBS for flood control purposes (Özgenç et al., 2024). Outdated regulations reinforce this mindset: in Australia, for instance, fire codes still classify vegetated walls as fire hazards, despite a lack of supporting evidence (Candido et al., 2021). In the United Kingdom, unclear policies regarding NBS have led to isolated and unmonitored initiatives (Dick et al., 2019).

Moreover, poorly communicated projects — such as the introduction of plants without involving employees in the process — risk being perceived as superficial marketing efforts, failing to achieve the intended outcomes (Gritzka et al., 2020).

4.6.3 Maintenance and Durability

All NBS require ongoing maintenance. Green roofs need frequent irrigation, and open vegetation areas demand regular cleaning (Reyes et al., 2024; Prodanović et al., 2024). In Singapore, high maintenance costs led to the replacement of vegetated walls with synthetic panels (Zhong et al., 2022).

Material deterioration also presents a challenge. In Berlin, wooden facades required frequent replacements due to humidity, which undermined projected financial returns (Zhong et al., 2022). The absence of post-implementation protocols can delay maintenance actions, escalating repair costs (Fastenrath et al., 2020). Some NBS are climate-specific, requiring costly adaptations (Özgenç et al., 2024).

Additionally, the ability of NBS to withstand extreme weather is often overestimated. Heatwaves, for example, increase plant mortality on green roofs, necessitating replanting (Reyes et al., 2024). Non-native species can introduce pests or cause soil erosion, harming local ecosystems (Yeo et al., 2020; Ausseil et al., 2022). Technologies like VR also require regular updates and maintenance, which can limit scalability (Mostajeran et al., 2021).

4.6.4 Data and Methods

The absence of reliable and standardized metrics threatens the credibility of NBS, posing obstacles to funding and large-scale adoption. For instance, VR stress-reduction studies have used salivary cortisol and heart rate as indicators, yet there is no consensus on the most appropriate measures (Yin et al., 2022; Chan et al., 2023). Air quality monitoring and subjective well-being surveys have also produced inconsistent results (Pereira et al., 2023; Kolokotsa et al., 2020).

Methodological inconsistencies deter investment. In Berlin, discrepancies in reported temperature reductions (ranging from 0.5°C to 2°C) prompted investors to withdraw from NBS projects (Zhong et al., 2022). Unexpected costs — such as green roofs consuming more water than anticipated — further strain resources (Zhang et al., 2023). Additionally, wetlands intended for flood control may inadvertently emit methane, undermining climate mitigation goals (Pereira et al., 2023).

Intangible benefits are also difficult to quantify. How, for example, can the value of a park that reduces stress yet contributes to rising local living costs be accurately assessed? Sustainable solutions sometimes drive real estate speculation, leading to irreversible social consequences (Fastenrath et al., 2020). Technical quality matters as well: VR environments with resolutions below 1080p or latencies exceeding 50 milliseconds reduce immersion by 40% (Chan et al., 2023), while sessions longer than 15 minutes caused nausea in 20% of participants (Kumpulainen et al., 2024).

However, the use of homogeneous samples limits generalization. Zhang and Lyu emphasize that such sampling does not represent the work environment, with age being the most impactful factor on the obtained results. Ausseil further criticizes the underrepresentation of social groups, while Yu warns of cultural bias in research restricted to specific geographic regions. Chan adds that brief interventions limit conclusions for assessing long-term effects, and Lopes states that single sessions do not measure cumulative impacts.

Meanwhile, White argues that reliance on self-reports complicates the analysis of results, depending on statistical artifacts to circumvent these situations. Furthermore, physiological measures are underutilized; only 30% of studies with occupational interventions used markers such as cortisol, while the others relied solely on participant questionnaires (Gritzka et al., 2020). Gritzka further emphasizes that differences in dosage, contexts, and metrics prevent the acquisition of concrete data for occupational health.

5. Discussion

The studies evaluated demonstrate that implementing NbS as an occupational management strategy offers substantial advantages, while also highlighting persistent challenges. Work environments enriched with natural elements, such as indoor vegetation and views of green landscapes, showed improvements in occupational and physical health, attributed to reductions in cortisol levels (Prodanović et al., 2024) and burnout symptoms (Gritzka et al., 2020). Additionally, Lei et al. (2021) and Ramm et al. (2024) demonstrated the positive impact of biophilic environments on productivity and cognitive performance. These findings reinforce the connection between NbS and workplace well-being. Importantly, they also align with the objectives of integrated QEHS management frameworks, which prioritize holistic well-being, operational efficiency, and environmental stewardship. Incorporating NbS directly supports the health and safety pillars of QEHS by improving air quality, reducing psychosocial risks, and fostering healthier work environments, while the environmental dimension is strengthened through ecological resilience and energy efficiency gains.

However, the successful implementation of such projects depends on technical expertise in ecology, architecture, and management, as well as overcoming the current shortage of skilled labor (Coletta et al., 2021; Reyes et al., 2024), which limits the execution of complex initiatives. To address this, interdisciplinary collaboration among architects, ecologists, occupational health specialists, and facility managers emerges as a critical facilitator, ensuring that NbS are effectively designed and maintained within QEHS systems.

The reduction in healthcare costs (Jimenez et al., 2021) and absenteeism (Candido et al., 2021) contrasts with the high upfront investments and operational expenses involved (Reyes et al., 2024; Zhong et al., 2022). Hybrid models emerge as a pragmatic solution, employing minimal vegetation or sensory substitutes like virtual reality to balance feasibility with impact (Mostajeran et al., 2021). Moreover, institutional leadership plays a pivotal role as a facilitator: when management commits to sustainability goals and employee well-being, the integration of NbS into corporate policies and QEHS protocols becomes more systematic and prioritized. Corporate champions can drive change, mobilize resources, and overcome internal resistance. Conversely, cultural resistance to green infrastructure — as seen in São Paulo (Özgenç et al., 2024) — underscores the need for public policies that incentivize NbS adoption through subsidies and regulatory updates (Dick et al., 2019). These measures can prevent such initiatives from being dismissed as superficial marketing efforts (Gritzka et al., 2020).

The effectiveness of NbS solutions also varies by geographic location. For example, heatwaves can increase plant mortality, driving up maintenance costs (Zhong et al., 2022). While artificial measures can be deployed in any environment with minimal upkeep (Zhong et al., 2022), prioritizing native species enhances the success of vegetative projects (Yeo et al., 2020). Furthermore, the unequal distribution of access to natural environments signals an urgent need for interventions that prevent social inequities from deepening (Sebestyén et al., 2023). Certification programs, such as WELL and LEED, serve as additional facilitators by providing recognized frameworks that standardize NbS implementation within occupational spaces. Although these frameworks require adaptation to local conditions (Candido et al., 2023), they offer structured pathways to align NbS initiatives with QEHS objectives, improving credibility and stakeholder buy-in.

VR emerges as a promising alternative for constrained environments, contributing to stress reduction (Chan et al., 2023) and lower absenteeism (Mostajeran et al., 2021). However, its dependency on software updates and recurring costs restricts large-scale application (Mostajeran et al., 2021). Moreover, studies have noted side effects during prolonged use, such as discomfort or nausea (Kumpulainen et al., 2024), suggesting VR is best employed alongside low-cost, natural interventions like potted plants (Hähn et al., 2021). Despite these limitations, VR can serve as an effective complement to physical NbS within integrated QEHS strategies, especially in spaces where natural elements cannot be readily incorporated.

A significant barrier remains the lack of methodological standardization, which hampers comparability across studies. Divergent metrics (Yin et al., 2022; Chan et al., 2023) and the underestimation of external variables (Zhang et al., 2023) highlight the importance of lifecycle analysis in project planning. Developing indicators that integrate physiological, economic, and environmental data is crucial to support informed strategic decision-making (Seddon et al., 2020). Standardized metrics would facilitate the integration of NbS into QEHS auditing processes, enhancing monitoring, compliance, and continuous improvement. Certifications like WELL and LEED provide valuable frameworks but must be adapted to local contexts (Candido et al., 2023). Simultaneously, government incentives remain essential, not only to reduce the financial burden of initial investments but also to formalize NbS within national health and safety regulations, as exemplified by Brazil's recent update to Regulatory Standard 01 (NR01). In parallel, educational institutions must train professionals capable of managing these complex projects (Coletta et al., 2021).

Future research should prioritize longitudinal studies to assess outcomes beyond the typical two-year horizon (Coletta et al., 2021). Comparative analyses across sectors — such as healthcare versus industry — could reveal critical contextual insights (Al Khatib et al., 2024; Oturakci, 2019). Furthermore, integrating artificial intelligence presents an exciting opportunity to adjust environments dynamically based on real-time physiological feedback (Ramm et al., 2024), offering new avenues for embedding NbS within smart QEHS management systems. Provided that ethical standards and accessibility are rigorously maintained, these innovations could substantially advance the precision and responsiveness of occupational health strategies.

6. Conclusion

This systematic review confirms that NbS offer significant potential to transform occupational environments, contributing to the integrated advancement of quality, health, safety, and sustainability goals. By fostering reductions in stress, cortisol levels, and burnout, alongside measurable improvements in cognitive function and productivity, NbS directly support the holistic objectives embedded within QEHS frameworks. Such integration advances not only organizational performance but also broader public health priorities, particularly as emerging regulations like Brazil's NR01 now formally recognize psychosocial risk management as a core institutional duty.

However, realizing this potential requires moving beyond isolated interventions toward systemic adoption strategies. Organizational leadership must champion NbS integration, aligning corporate policies with environmental and health priorities. Interdisciplinary collaboration is equally essential, bridging expertise from architecture, ecology, occupational health, and engineering to design context-sensitive solutions. Standardized metrics and adaptable certification systems such as WELL and LEED can further embed NbS within QEHS auditing and compliance processes, ensuring accountability and continuous improvement.

Equally, policy incentives and public-private partnerships must address structural barriers, particularly the shortage of skilled labor and uneven access to natural solutions across different socioeconomic settings. Investment in specialized training programs and academic curricula will be critical to cultivate the professional capacity required for effective NbS implementation.

Looking ahead, future research should prioritize longitudinal assessments to evaluate the sustained impacts of NbS over time, as well as comparative analyses across diverse occupational sectors to tailor strategies more precisely. Emerging technologies, including artificial intelligence and real-time environmental monitoring, represent promising frontiers for dynamically optimizing workplace conditions in alignment with QEHS objectives.

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6 CONSIDERAÇÕES FINAIS

Esta dissertação teve como objetivo analisar criticamente o papel das Soluções Baseadas na Natureza (SbN) como estratégia de gestão integrada da qualidade, meio ambiente, saúde e higiene ocupacional (QMSH), por meio de duas abordagens complementares: o desenvolvimento de um Sistema de Suporte à Decisão baseado em lógica fuzzy (SSDF) e a realização de uma revisão sistemática da literatura científica.

O primeiro artigo propôs um modelo inovador, o SSDF, capaz de recomendar intervenções baseadas na natureza em ambientes ocupacionais, considerando indicadores ambientais e de saúde. A aplicação do sistema em um estudo de caso real demonstrou sua capacidade de lidar com incertezas inerentes aos ambientes de trabalho e fornecer recomendações práticas para a promoção da saúde e do bem-estar dos trabalhadores. A utilização da lógica fuzzy mostrou-se uma abordagem eficiente para integrar variáveis subjetivas e objetivas, como conforto térmico, acústico, iluminação, absenteísmo, perigos e condições insalubres, possibilitando uma gestão mais estratégica e adaptável do ambiente ocupacional. Apesar de suas potencialidades, o SSDF também revelou limitações, principalmente relacionadas à dependência de dados de alta qualidade e à necessidade de ajustes para diferentes contextos ocupacionais.

O segundo artigo complementou o trabalho ao consolidar o estado da arte sobre a aplicação de SbN em ambientes de trabalho. A revisão sistemática identificou benefícios robustos associados à implementação de SbN, como a redução do estresse, melhoria da concentração, aumento da produtividade e diminuição do absenteísmo. No entanto, também revelou barreiras significativas, incluindo a falta de conhecimento técnico, custos de implementação, e a ausência de integração sistemática com modelos de gestão já estabelecidos. Esses achados reforçaram a pertinência de ferramentas como o SSDF, capazes de apoiar a adoção de SbN de forma mais estruturada e baseada em evidências.

De forma integrada, os dois estudos demonstram que as SbN constituem uma estratégia promissora para ambientes ocupacionais, mas sua implementação eficaz depende tanto do desenvolvimento de instrumentos técnicos de suporte à decisão quanto da superação de barreiras organizacionais e culturais. Assim, esta dissertação não apenas preenche lacunas teóricas ao sistematizar o conhecimento existente, mas também oferece uma contribuição prática ao disponibilizar um modelo aplicável para a promoção da saúde, sustentabilidade e qualidade em ambientes de trabalho.

Como limitações, destaca-se que o SSDF foi validado em um único estudo de caso, sendo necessária sua aplicação em contextos variados para comprovar sua robustez e escalabilidade. Além disso, a revisão sistemática apontou a necessidade de maior produção científica focada especificamente na interface entre SbN e ambientes de trabalho, indicando uma linha promissora para futuras investigações.

Espera-se que os resultados desta dissertação possam apoiar gestores, projetistas e profissionais de saúde ocupacional na adoção de práticas mais sustentáveis e centradas no bem-estar humano, contribuindo para a construção de ambientes laborais mais resilientes, saudáveis e eficientes.

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