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Workplace Well-Being Through Nature-Based Solutions: A Fuzzy Framework for Decision-Making

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Abstract: The rise in performance and health concerns presents a complex challenge to 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 designs in workplaces. This study addresses this issue by introducing a Type-1 Interval Fuzzy Set (IFS) framework to assess workplace health, and recommends Nature-Based Solutions (NbS) for enhancement. The proposed framework comprises two fuzzy subsystems targeting environmental comfort and occupational health that are integrated into a third subsystem to provide tailored NbS recommendations. A case study conducted in a coworking space validated the framework's practical application, revealing significant improvements in environmental and occupational conditions. Key findings include a reduction in absenteeism, enhancement in employee satisfaction, and creation of more comfortable and restorative environments. Recommendations, such as green walls, indoor gardens, and natural light filters, have been shown to effectively mitigate discomfort and promote well-being. The framework demonstrated flexibility in managing uncertainties, optimizing resource allocation, and providing targeted interventions for workplace conditions. These results highlight the framework's potential as a robust decision-support tool for improving workplace health and well-being through systematic and evidence-based strategies.

Keywords: workplace well-being; environmental health; nature-based solutions; fuzzy logic; artificial intelligence

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1. Introduction

A positive and supportive work environment significantly contributes to employee well-being and performance. However, the competitive and output-driven nature of many workplaces often exacerbates stress levels, leading to adverse health outcomes such as burnout, depression, and anxiety [1]. This highlights the necessity of cultivating balanced environments to mitigate negative impacts and enhance employee resilience [2]. Evidence shows that indoor environmental quality plays a critical role in this effort, and exposure to nature indoors is consistently associated with improved well-being and productivity [3,4].

Biophilic Design (BD) has emerged as a pivotal strategy for integrating Nature-based Solutions (NbS) into the human infrastructure to enhance workplace health and sustainability. By embedding natural elements into the design, BD leverages the restorative effects of nature to promote mental health and productivity [5]. Despite their potential, Lei et al. [5] and Alipour and Khoramian [6] emphasize the need for tailored guidelines and assessment

methods to ensure the effective implementation of biophilic principles across diverse workplace typologies. Addressing these challenges is crucial, as NbS not only enriches physical spaces but also supports mental well-being through enhanced connectivity to nature [7].

While this study primarily focuses on plant-based interventions and direct applications of nature within workplace interiors, it is important to acknowledge broader aspects of biophilic design that extend beyond the inclusion of vegetation. Research indicates that nonliving geometrical patterns inspired by nature, such as fractal designs, can significantly enhance the restorative potential of built environments [8,9]. However, these aspects remain outside the scope of this study, which is centered on the practical implementation of NbS through plant life and related natural elements.

The role of NbS in addressing workplace challenges extends beyond aesthetics. Studies suggest that interventions like indoor greenery and natural light improve air quality, reduce stress, and foster overall employee satisfaction [10,11]. Additionally, workplace health and well-being encompass various facets, including environmental quality, task perceptions, and organizational dynamics [12]. Integrating green spaces into design planning enhances workplace restoration, aligned with the principles of human-nature interaction [13].

This study addresses this critical gap by systematically integrating biophilic design principles with decision-making tools to enhance workplace health. Leveraging fuzzy logic, it offers a robust framework for managing the complexities and uncertainties inherent in workplace conditions. The proposed fuzzy decision support system (FDSS) is designed to recommend NbS that are scalable, resource-efficient, and adaptable to diverse organizational needs. By combining theoretical insights with practical applications, this study contributes to a novel approach for improving 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 2024”)) and (limit-to (language, “english”)). This search resulted in 267 articles, which were preliminarily screened. After excluding articles outside the scope, 17 articles were selected, as discussed below.

Recent studies have increasingly emphasized the transformative potential of natural environments in the workplace. Latini et al. [14] examined biophilic design strategies through immersive virtual environments, demonstrating improvements in workplace cognitive performance and well-being. Their findings underscore the importance of integrating multisensory natural elements into office design. Similarly, Song et al. [15] highlight the positive influence of biophilic hotel lobbies on both employee productivity and guest satisfaction, providing further evidence of nature’s restorative effects in work-related settings.

Biophilic design is also recognized for its ecological and economic benefits. Yang et al. [16] explored how nature-based design principles enhance peri-urban agricultural areas and contribute to healthier and more sustainable built environments. Additionally, Errante [17] reviewed NbS applications in urban settings and identified their role in mitigating urban heat islands and improving air quality.

Other investigations have reported mixed outcomes. For instance, Gritzka et al. [1] found consistent mental health improvements through workplace nature-based interventions, while recovery outcomes varied based on intervention type. Miles et al. [18] observed

reductions in illnesses and mood improvements tied to workplace exposure to natural environments, reinforcing the need for context-sensitive designs.

Yu et al. [19] investigated the use of eco-friendly physical environments to reduce employee burnout and enhance job satisfaction in hospitality settings. They emphasized the role of NbS in fostering psychological resilience and promoting health. Similarly, Lefosse et al. [20] explored the upscaling of biophilic design using systematic metrics, showing its scalability for urban planning.

These studies collectively underscore the multidimensional benefits of NbS and biophilic design in workplaces while also highlighting gaps in their implementation and evaluation. This study addresses these challenges by introducing an FDSS to optimize workplace well-being through systematic and scalable nature-based strategies.

3. Theoretical Framework

3.1. Concept of Nature-Based Solutions

NbS are innovative strategies inspired by natural processes designed to address societal challenges while enhancing ecosystem services and human well-being [21]. In workplace environments, NbS includes interventions, such as green walls, biophilic design, and natural light optimization, which have been linked to improvements in psychological and physiological well-being [22]. Zhang et al. [23] demonstrated the value of biophilic play spaces in urban areas, and underscored the role of NbS in fostering community well-being and environmental sustainability. Similarly, AlAli et al. [24] explored NbS in urban landscapes, emphasizing their capacity to enhance workplace health and productivity through biomimetic design principles.

3.2. Fuzzy Logic in Decision-Making

Fuzzy logic offers a mathematical framework for handling uncertainties and ambiguities inherent in real-world scenarios [25]. Its capacity to process imprecise data makes it particularly suitable for workplace decision-making where comfort and health are inherently subjective variables. Gao et al. [26] demonstrated how fuzzy logic can optimize resource allocation in decision-making systems for urban design. In environmental engineering, Vojvodíková et al. [27] validated the effectiveness of fuzzy systems in addressing urban ecological challenges by integrating NbS into resource management frameworks.

3.3. Integration of Biophilic Design and NbS

Biophilic design integrates nature into built environments, complementing NbS by fostering human-nature connections. Gertik and Karaman [28] revealed that biomimetic approaches such as fractal-based urban designs enhance environmental satisfaction and health outcomes. Moreover, Schaffernicht et al. [29] identified the synergy between biophilic design and NbS in addressing heat-related workplace challenges, highlighting the importance of natural light and vegetation in enhancing thermal comfort.

3.4. Bridging Literature and Model Development

Existing research highlights the transformative potential of integrating NbS and biophilic designs to enhance workplace well-being. However, these studies often lack systematic frameworks for application. The proposed FDSS bridges this gap by synthesizing empirical data using fuzzy logic principles to deliver tailored NbS recommendations. This integration aligns with the evidence-based methodologies advocated by Andreucci et al. [21] and Lefosse et al. [20], which offer a structured approach to addressing uncertainties in workplace health interventions.

4. Methodology

The decision-support system was developed using fuzzy logic to handle the uncertainties inherent in workplace evaluations, ensuring scalable, resource-efficient, and tailored recommendations for diverse organizational needs. The FDSS architecture includes three subsystems: two focused on environmental comfort and occupational health and a third that synthesizes their outputs to recommend NbS.

4.1. Variables and Parameter Selection

The input variables selected for this study serve as critical indicators of workplace health and environmental quality. These variables, identified through an extensive review of related works, directly inform the recommendations for NbS. The following key inputs were used:

- Thermal Comfort: Influences well-being, productivity, and the overall workplace comfort. Appropriate temperature ranges (21–27 °C) contribute to efficient daily activities and employee satisfaction [30].
- Acoustical Comfort: Excessive noise levels (30–53 dB) can lead to stress and distraction, adversely affecting mental health and concentration. Ensuring optimal acoustic conditions is essential for workplace productivity [31,32].
- Lighting Comfort: Proper lighting (300–1000 lux) supports visual efficiency and mental health by aligning with circadian rhythms, thereby enhancing mood and sleep quality [33].
- Absenteeism: Measured as the frequency of work absences (2–8%); absenteeism serves as a proxy for workplace health conditions. Reducing absenteeism through targeted health interventions ensures continuous operation [34,35].
- Hazardousness: Evaluates risks from environmental and occupational hazards (1–8/10), necessitating mitigation measures to ensure a safer work environment [36,37].
- Unhealthiness: Addresses harmful environmental conditions such as air pollutants that contribute to workplace discomfort and health issues (1–8/10) [38].

These input variables were carefully selected for their quantifiability and relevance to workplace health and well-being. Triangular membership functions were defined for each variable to enable precise modeling, and Min-Max scaling was applied to standardize their ranges, ensuring consistency across diverse workplace scenarios.

The FDSS architecture incorporates the following three subsystems: The first two subsystems evaluate environmental comfort (thermal, acoustical, and lighting comfort) and occupational health (absenteeism, hazardousness, and unhealthiness). The outputs from these subsystems are integrated into a third subsystem, which synthesizes recommendations for NbS across the five priority levels, as detailed in Section 4.5. This systematic structure ensures robust decision-making tailored to the complexities of workplace environments.

4.2. Membership Functions

To effectively quantify and address uncertainties in the FDSS, triangular-shaped membership functions were utilized. These functions enable the FDSS to manage imprecise and subjective input data, ensuring the robust modeling of workplace health and environmental quality indicators. Unlike binary membership functions in classical logic, which assign values of either 0 or 1, fuzzy logic provides a continuous membership interval between 0 and 1, accommodating gradations and ambiguities typical of real-world phenomena [39,40]. Triangular membership functions employed in this study are defined by three key parameters: '*a*' and '*c*': represent the base endpoints of the triangle, marking the minimum and maximum bounds of the membership function; '*b*': denotes the peak of the triangle, corresponding to the maximum degree of membership (value of 1). The triangular

shape facilitates a gradual transition of membership values across the defined range, with higher certainty near the peak and increasing uncertainty toward the edges. This design is particularly suited for workplace indicators where variability and partial truth are common (Figure 1).

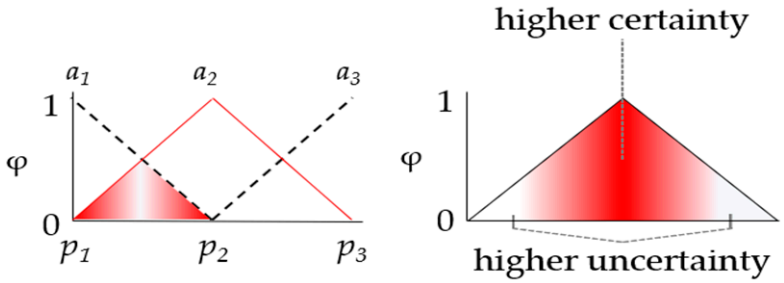


Figure 1. Triangular-shaped membership functions for concept modeling.

Figure 1 illustrates this triangular structure, showing how regions near the peak exhibit high certainty (membership value near 1), while those near the base edges transition toward 0, capturing the uncertainty in the input data.

4.3. Inference Engine

The inference engine in the FDSS translates input variables into actionable outputs through the systematic application of fuzzy logic rules. This process leverages a Type-1 Mamdani inference engine, also known as the Max-Min method, to model the relationships between environmental and occupational health indicators and generate tailored recommendations for NbS. Fuzzy rules form the foundation of the inference engine, mapping the linguistic terms of the input variables (e.g., "low", "medium", and "high") to the outputs through IF-THEN propositions [41]. Logical operators are applied to handle input combinations: conjunction (AND) uses the minimum value of the input variables in the rule's antecedent, and disjunction (OR) takes the maximum value of the input variables in the rule's antecedent.

The Max-Min method is particularly effective in managing the uncertainties inherent in workplace evaluations. By applying these fuzzy logic operators, the system derives intermediate fuzzy sets that reflect the combined effect of the input variables on the outputs [42]. Once the fuzzy outputs are generated, the centroid method is employed for defuzzification, converting the fuzzy sets into crisp numerical values. This approach ensures precise actionable recommendations that align with workplace-specific needs [43]. The centroid method calculates the weighted average of the fuzzy set, providing intuitive and reliable outputs validated in various fields, including intelligent systems and engineering applications. The FDSS inference process operates through three sequential subsystems, as illustrated in Figure 2.

- FDSS1: Focuses on environmental comfort, processing input variables such as thermal comfort, acoustical comfort, and lighting comfort. These inputs are categorized into linguistic terms ('low', 'medium', and 'high') based on predefined thresholds derived from expert consultations and the literature. The subsystem evaluates these inputs using defined fuzzy rules to generate an intermediate environmental comfort score.
- FDSS2: Evaluates occupational health by integrating input variables such as absenteeism, hazardousness, and unhealthiness. Using the same fuzzy logic principles, this subsystem produces an occupational health score.
- FDSS3: Synthesizes outputs from FDSS1 and FDSS2 to generate the final NbS recommendations, including green walls, indoor gardens, natural elements, natural light filters, nature sounds, and natural rest zones.

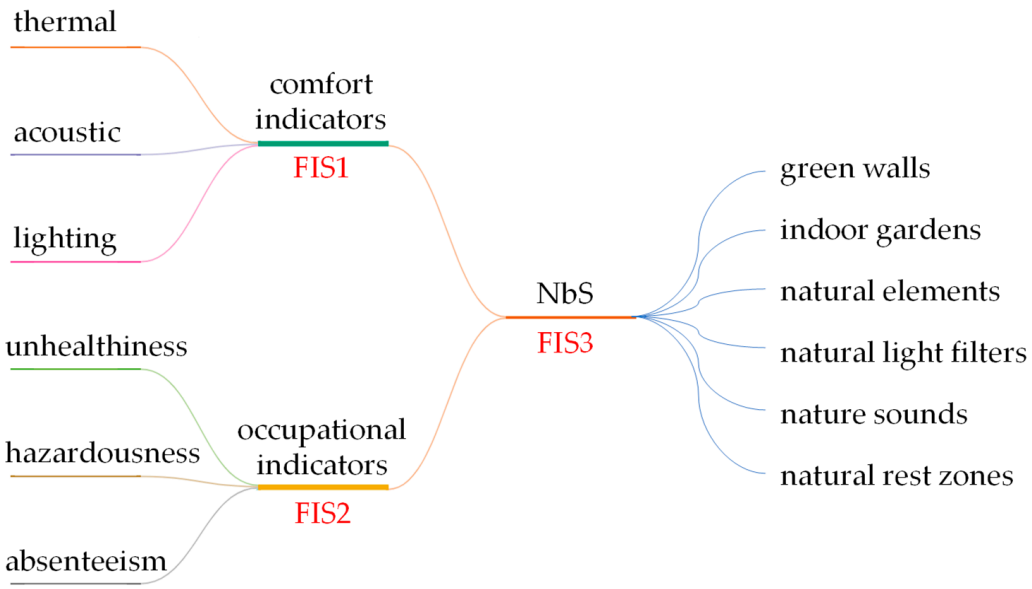


Figure 2. Fuzzy-based DSS for recommending NbS to improve workplace health and well-being.

4.4. Fuzzy Rules

To manage system complexity, two inference subsystems—FDSS1 and FDSS2—were developed to evaluate environmental comfort and occupational health, respectively. These subsystems employ distinct fuzzy rule bases to map the input variables to the output variables using defined linguistic classifications. The outputs of FDSS1 and FDSS2 are integrated into a composite system, FDSS3, which provides actionable recommendations for NbS based on workplace conditions. The relationships between the input variables and their respective output variables are defined by fuzzy rules, as illustrated in Table 1.

The development of the fuzzy rule base follows a systematic process.

- Selection of Input Variables: Based on literature reviews and expert consultations, key variables were chosen for their relevance to workplace well-being. FDSS1 incorporates thermal, acoustic, and lighting comfort, while FDSS2 focuses on absenteeism, hazardousness, and unhealthiness.
- Categorization of Linguistic Levels: Each input variable was categorized into three levels ('low', 'medium', and 'high') using predefined thresholds derived from scientific studies and practical expertise.
- Rule Construction: Fuzzy logic operators (e.g., AND and OR) were employed to create relational rules. For example, the rule "If thermal comfort is 'low' AND acoustical comfort is 'low', THEN environmental comfort is 'very low'" and encapsulates logical relationships between variables.
- Preliminary Testing and Refinement: Simulated scenarios were used to validate the rule base. Iterative adjustments were made to ensure accuracy and responsiveness to diverse workplace conditions.

The outputs from FDSS1 and FDSS2 are synthesized in FDSS3 to generate comprehensive NbS recommendations. Table 2 presents the composite rule base that integrates the environmental comfort and occupational health scores to determine the level of intervention required.

This table maps combinations of environmental comfort and occupational health to output levels, with lower scores indicating a greater need for intervention. For instance, if both environmental comfort and occupational health are 'very low', the NbS priority level is the highest (score of 5). Conversely, when both conditions are 'very high', the priority level is minimal (score of 1).

Table 1. Rule base for FDSS1 and FDSS2.

Input #1	Input #2	Input #3	Output
low	low	low	very low
		medium	very low
		high	low
	medium	low	low
		medium	medium
		high	medium
	high	low	low
		medium	medium
		high	medium
medium	low	low	very low
		medium	medium
		high	medium
	medium	low	medium
		medium	medium
		high	medium
	high	low	medium
		medium	medium
		high	very high
high	low	low	medium
		medium	medium
		high	high
	medium	low	medium
		medium	medium
		high	high
	high	low	high
		medium	very high
		high	very high

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

4.5. NbS Recommendations

Table 3 presents a structured framework for NbS tailored to workplace conditions, as assessed by FDSS3. These recommendations integrate environmental comfort and occupational health indicators, and categorize NbS into five priority levels. This stratification ensures that resources are judiciously allocated, with interventions escalating in intensity based on the severity of the workplace conditions.

Table 3. NbS for improving well-being in the workplace.

NbS	Recommendations for Priority Actions Based on FDSS3 Output				
	Set 1 in Optimal Scenarios, Solutions for Continuous Improvement Are Recommended:	**Set 2 for a High Baseline, Maintaining and Elevating the Current Standards Is Paramount:**	**Set 3 with Moderate Levels, There's Room for Improvement Without Drastic Interventions:**	**Set 4 for Environments with Lower Well-being Indices, More Robust Measures Are Necessary:**	**Set 5 in Extreme Scenarios, Comprehensive Interventions Are Crucial:**
green walls				install vertical gardens to promote a visually appealing workspace and augment air quality	
indoor gardens			integrate plant arrangements to enhance aesthetic appeal and air quality		
natural elements	optimize the use of natural light, and introduce natural textures and materials to reinforce the connection with nature				
natural light filters	use adjustable blinds or filters to control and optimize natural light exposure				
nature sounds	use soundscapes to mask unpleasant noises and create a calming atmosphere				
natural rest zones					create comfortable spaces with elements of nature for short breaks

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), enhances ambiance and mitigates 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, small indoor gardens or vertical green walls are installed 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, larger-scale indoor gardens and vertical plant systems can be deployed to transform the 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, natural rest zones equipped with plants, ergonomic furniture, and natural light can be created to provide employees with restorative space.

4.5.2. Key Details of Specific Recommendations

The proposed NbS includes several targeted interventions that are tailored to address specific workplace conditions. Green walls, or vertical gardens, are emphasized across all sets due to their dual role in improving air quality and aesthetics. The complexity and scale of these installations increase progressively depending on workplace needs. Similarly, indoor gardens begin as small planters in Set 3 and develop into full-fledged green spaces in Set 5, providing substantial support for both mental and physical health.

Natural elements, such as wooden finishes, stone textures, and foliage, are incorporated to align with biophilic principles. These features are particularly emphasized in Sets 1 and 2, which offer cost-effective and scalable options for enhancing workplace aesthetics and well-being. Natural light filters, including adjustable blinds or foliage curtains, are universally recommended across all sets. These interventions optimize the lighting conditions, reduce eye strain, and contribute to a healthy visual environment.

Nature sounds, introduced through audio systems playing natural soundscapes, are recommended in Sets 1 and 2. These soundscapes improve focus and reduce stress, contributing to a more serene workplace environment. Lastly, natural rest zones are introduced comprehensively in Set 5. These dedicated spaces for relaxation and stress recovery are particularly vital in high-stress workplace settings, offering employees a restorative environment that enhances their well-being and productivity.

4.5.3. Rationale and Application

The recommendations in Table 3 prioritize solutions that are carefully designed to be scalable, resource conscious, and holistic. Scalability ensures that interventions can begin with small-scale implementations in optimal scenarios and escalate to more significant measures under challenging conditions. This adaptability allows workplaces to tailor their level of intervention based on specific requirements and available resources.

Resource consciousness is another key focus that encourages efficient use of financial and spatial resources. By aligning the intensity and scale of interventions with the unique needs of each workplace, the recommendations aim to deliver impactful results without imposing unnecessary burden.

Finally, the recommendations adopt a holistic approach by integrating enhancements in environmental comfort with improvements in occupational health. This balanced strategy ensures comprehensive well-being outcomes, addressing both the physical environment and broader health-related needs of employees.

4.6. Validation of the FDSS

To validate the effectiveness of the FDSS, a simulation algorithm was developed, as provided in the Supplementary Materials. This Python-based simulation tool allows users to input environmental and occupational parameters such as thermal comfort, acoustical comfort, lighting comfort, absenteeism, hazardousness, and unhealthiness. The algorithm categorizes these inputs into linguistic levels ('low', 'medium', and 'high') based on predefined thresholds derived from technical literature. Using inference rules, the tool simulates the impact of selected NbS, such as green walls, indoor gardens, and natural light filters, on workplace conditions. Post-intervention, the algorithm evaluates the efficiency scores for each parameter, offering a quantitative assessment of NbS recommendations.

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 the parameter setting and validation steps.

5.1. Practical Application

For 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. [44], 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.

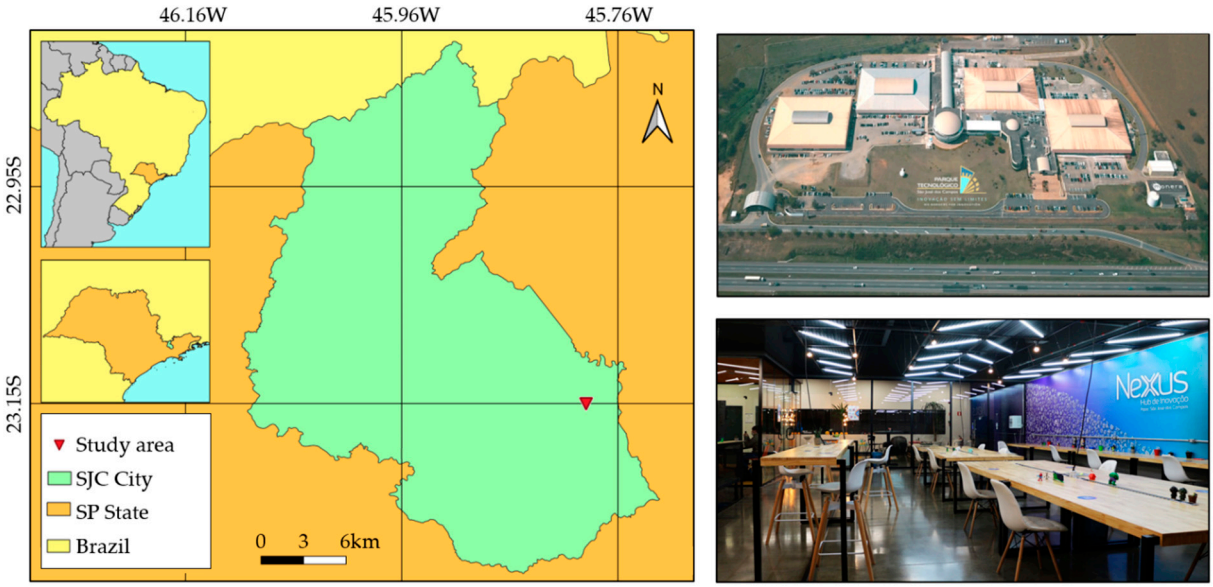


Figure 3. Coworking space at the Technological Innovation Park.

5.2. Parameter Standardization

This workplace is dedicated to coworking and is 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 lists the conditions, reference scores, and parameters (a, b, and c) for each indicator, providing a comprehensive view of how variables are treated within the fuzzy decision support system. The derivation of these reference scores involved several key steps. First, literature reviews were conducted to determine the typical ranges for each indicator within workplace environments. These reviews provide a foundation for establishing thresholds for the low, medium, and high categories for each variable. Second, expert consultation played a critical role in refining these ranges. Ergonomists with extensive experience in workplace design contributed to aligning variables and thresholds with best practices and research findings, ensuring that the selected measures optimize employee well-being and productivity. Occupational health specialists added insights into workplace risks, such as exposure to hazardous conditions, absenteeism trends, and unhealthiness factors, grounding occupational indicators in empirical health data. Additionally, environmental engineers specializing in indoor environmental quality assessed variables like

thermal comfort, lighting, and acoustical quality to ensure that the thresholds met both industry standards and practical implementation requirements. Third, a statistical analysis was applied to determine the central tendency measures (mean and median) and dispersion (standard deviation) for each indicator. This step defines the optimal ranges that accurately represent typical workplace conditions. Finally, the parameter settings for the membership functions were established. In this framework, parameters a and c define the endpoints of the triangle base, while b represents the peak corresponding to the most typical or central value within the range. Each score reflects a consensus derived from empirical data and expert judgment, ensuring scientifically robust and practically relevant recommendations.

Table 4. Fuzzy triangle-shaped membership function.

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

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

To illustrate the operation of the FDSS, the following If-Then rules were employed to map the input parameters to the output recommendations:

- Rule Example 1: If thermal comfort is 'low', acoustical comfort is 'medium', and lighting comfort is 'high', then the environmental comfort is classified as 'medium'.
- Rule Example 2: If absenteeism is 'low', hazardousness is 'medium', and unhealthiness is 'high', then occupational health is classified as 'low'.
- Rule Example 3: If environmental comfort is 'high' and occupational health is 'medium', then NbS recommendations include moderate interventions (e.g., additional green walls or optimized natural light).

For the provided case study, the input parameters—thermal comfort (25 °C, classified as 'medium'), acoustical comfort (53 dB, classified as 'low'), and lighting comfort (700 lux, classified as 'medium')—were processed using the Mamdani inference engine. The rule evaluation combines these inputs to yield an environmental comfort output of 'medium'. Similarly, for occupational health indicators—absenteeism (3%, classified as 'low'), hazardousness (1/10, classified as 'low'), and unhealthiness (1/10, classified as 'low')—the output occupational health score was classified as 'high'.

Defuzzification was performed using the centroid method, which translates fuzzy outputs into crisp values. The final NbS recommendations for the coworking space were

categorized under Set 3 (moderate improvements), with specific suggestions, including the installation of indoor gardens to enhance air quality and aesthetic appeal and the use of natural light filters to optimize lighting conditions. This systematic approach demonstrates the FDSS's capacity to address complex workplace scenarios effectively and flexibly.

5.3. Parameter Assessment and NbS Recommendations

The coworking office underwent a thorough assessment, which revealed potential discomfort in terms of thermal comfort, as 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 by introducing natural elements that not only improve air quality, but also provide aesthetic benefits, enhancing the overall work environment [45].
- 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 [46].
- For the acoustic challenge, implementing nature sounds, like birdsong or flowing water, becomes crucial to mitigate ambient noise, promoting relaxation and concentration [47].
- To counter the lighting discomfort, the strategic use of natural light filters that diffuse sunlight is recommended. This not only creates a softer lighting environment but also reduces eye strain and enhances visual comfort.

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

5.4. NbS Valiation

The NbS recommended by the FDSS were evaluated through a dedicated simulation code (available as Supplementary Materials) to assess their effectiveness in improving workplace well-being metrics. Based on the initial pre-intervention conditions, the FDSS suggested implementing NbS from a moderately intensive set, as detailed in Section 5.3.

The simulated application of these interventions, conducted using the Supplementary Materials [30,31,48–51], demonstrated notable enhancements across the workplace metrics. Thermal comfort achieved a high-efficiency level of 90%, driven by the thermal regulation capabilities of green walls and indoor gardens. Acoustic comfort improved to a medium level with a 70% efficiency, attributed to the sound absorption properties of the green walls. Lighting comfort advanced to a high category with an 80% efficiency gain facilitated by the introduction of natural light filters. Indicators of occupational health also showed substantial progress; absenteeism and unhealthiness improved to medium levels, reaching efficiencies of 80% and 75%, respectively, highlighting the broad impact of biophilic design on employee well-being. Hazardousness remained low, albeit with a modest increase in efficiency of 60%.

These findings underscore the efficacy of the FDSS framework in systematically guiding the application of NbS to address workplace challenges. The demonstrated improvements validate the framework's potential as a robust and scalable tool for decision-makers, providing actionable insights to enhance environmental and occupational conditions while fostering sustainability and employee health.

5.5. Practical Insights and Lessons Learned

The practical application of the FDSS framework to a case study provides valuable insights into both the system's operational strengths and areas for future refinement. The implementation highlighted several key lessons that are relevant to workplace health and well-being initiatives.

The FDSS demonstrated flexibility in addressing diverse workplace conditions, effectively integrating environmental and occupational health indicators. Its ability to accommodate uncertainties in data and generate context-specific recommendations was pivotal for ensuring targeted interventions. For example, the application of green walls and natural light filters in the coworking space exemplified the framework's capacity to deliver tailored solutions.

The simulation results validated the efficacy of NbS, showing measurable improvements across the key indicators. Notably, thermal comfort and lighting conditions were enhanced, while absenteeism rates showed promising reductions. These quantifiable outcomes underscored the framework's potential as a decision-support tool.

The framework's modular structure allows for scalability, enabling its application to workplaces of varying sizes and complexity. This feature ensures that even organizations with limited resources can implement incremental changes aligned with their capacity, demonstrating the FDSS's resource-conscious design.

The case study revealed opportunities to enhance the FDSS, such as integrating real-time monitoring systems for dynamic feedback and incorporating broader psychosocial indicators. Additionally, the inclusion of cost-benefit analyses could further strengthen the framework's utility in organizational decision-making.

By systematically addressing workplace challenges through evidence-based strategies, the FDSS framework offers a robust foundation for promoting health, well-being, and productivity. The lessons learned from its practical application not only validate its current design, but also provide a roadmap for future iterations and broader implementation.

6. Discussion

6.1. 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.

A 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 the ambiguity and subjectivity inherent in comfort limits, which can vary significantly from person to person. In the context of this case study, 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 that by Tsiutsiura et al. [52] corroborate the effectiveness of fuzzy systems in assessing comfort in environments with variable subjective elements, specifically in apartment buildings. Additionally, Menyhárt and Kalmár [53] 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.

While the FDSS successfully focuses on plant-based solutions and indoor greenery to address workplace conditions, it does not incorporate nonliving geometrical patterns inspired by nature, such as fractal designs, which are increasingly recognized for their restorative potential [8,9]. This limitation reflects the scope of the current study, which prioritizes practical applications of NbS centered on vegetation. Future research should investigate the integration of these nonliving biophilic elements to enhance workplace health interventions further, especially in settings where natural vegetation may not be feasible.

The FDSS framework offers several significant benefits and advantages in addressing workplace health and well-being. First, the integration of fuzzy logic with biophilic design principles represents an innovative approach to managing the complexities and uncertainties inherent in workplace environments. Unlike conventional decision-making systems, the FDSS accommodates subjective and imprecise variables, such as thermal comfort and lighting quality, delivering recommendations that are both flexible and robust.

Second, the system's ability to incorporate Nature-Based Solutions (NbS) ensures that recommendations align with sustainable and health-promoting workplace practices. The proposed framework enhances workplace conditions by offering evidence-based, resource-conscious solutions that are scalable to diverse organizational contexts. For example, interventions like green walls and natural light filters address specific environmental challenges while fostering employee satisfaction and productivity.

Third, the FDSS's modular structure, comprising separate subsystems for environmental comfort and occupational health, facilitates targeted assessments. This design allows decision-makers to prioritize areas of improvement efficiently, reducing implementation costs and ensuring judicious use of resources. The framework also advances the state of building science by providing a systematic and quantifiable method for integrating NbS into workplace management strategies.

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 of the 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 in which 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 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 in real-world scenarios. While the case study presented in this paper demonstrates its potential, broader validation across various workplace settings is necessary to ensure 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 may 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 summary, while the FDSS offers a novel approach to enhance workplace health and well-being 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.

6.2. Comparison with Prior Research

The findings of this study align with and extend the existing research on Nature-Based Solutions (NbS) and biophilic designs in workplace environments. Specifically, the study reinforces the well-documented link between workplace well-being and environmental conditions while also addressing gaps in the application of systematic, evidence-based frameworks like fuzzy logic.

The implementation of NbS, such as green walls and natural light filters, aligns with prior studies that highlight the positive impact of biophilic interventions on employee satisfaction and well-being. For example, Ogbonnaya et al. [54] demonstrated that high-performance workplace practices incorporating NbS significantly improved employee health and well-being by fostering a restorative work environment.

Similarly, Bennett [55] proposed that cultivating psychosocial and interpersonal conditions through environmental interventions enhances workplace wellness. Our study's findings echo this sentiment, demonstrating how green infrastructure not only improves physical environmental metrics but also contributes to psychological benefits, such as reduced stress and increased satisfaction.

While earlier research primarily focused on qualitative assessments of workplace interventions [56], this study uniquely integrates fuzzy logic to quantify and systematically address workplace complexities. The inclusion of measurable parameters and computational decision-making represents a novel advancement over more subjective methodologies.

Furthermore, unlike prior work that often emphasizes specific interventions in isolation [57], our framework holistically evaluates multiple dimensions—thermal, acoustic, and lighting comfort—demonstrating broader applicability across diverse workplace environments.

A noteworthy divergence from Xiao and Cooke [58] is the contextual adaptability of interventions. Their study suggested that human resource management (HRM) system consistency plays a critical role in employee well-being. Our study, however, demonstrates that even in the absence of rigid HRM frameworks, adaptable NbS tailored through fuzzy logic can yield significant improvements in well-being.

6.3. Limitations and Future Directions

This study, while innovative in applying a fuzzy inference system to recommend NbS for workplace health and well-being, has several limitations previously described as weaknesses of the FDSS, which include 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 well-being, future research should focus on the following areas:

- Exploring the Integration of Nonliving Biophilic Elements: Incorporating fractal patterns and geometrical designs inspired by nature as part of the NbS framework. These elements, supported by research such as Taylor [8] and Joye [9], have demonstrated the potential for stress reduction and aesthetic enhancement. This direction could expand the scope of biophilic design to environments where living vegetation is limited or impractical.
- 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 the 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 to 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 well-being 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 the integration

of these variables into a 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.

7. Conclusions

This study introduces a novel FDSS framework that integrates NbS with biophilic design principles to address workplace health and well-being. By systematically evaluating environmental and occupational health indicators through a fuzzy logic approach, the framework offers scalable and adaptable solutions tailored to diverse workplace conditions. The FDSS uniquely combines theoretical rigor with practical applicability, bridging the gap between empirical research and real-world implementation.

A case study conducted within a coworking space validated the framework's potential by demonstrating significant improvements in thermal comfort, lighting quality, and acoustical conditions, along with reductions in absenteeism and enhanced employee satisfaction. NbS recommendations, such as green walls, indoor gardens, and natural light filters, have proven effective in addressing workplace challenges and fostering a healthier and more productive environment. These findings align with prior research on the restorative and motivational impacts of biophilic design, while extending the discourse by incorporating fuzzy logic as a robust tool to manage decision-making uncertainties.

Despite its promising outcomes, the FDSS's reliance on high-quality data, limited validation scope, and the need for broader indicator integration underscore areas for future enhancement. Expanding validation across various workplaces, integrating additional psychosocial and environmental indicators, and incorporating cost-benefit analyses will further strengthen the framework's applicability and impact. While the FDSS focuses on plant-based and traditional NbS interventions, it does not incorporate nonliving geometrical patterns inspired by nature, such as fractal designs, which have been shown to positively influence stress reduction and visual aesthetics. Recognizing this limitation, future research should explore the integration of these elements to expand the potential applications of NbS. For example, fractal-inspired architectural elements may be particularly useful in environments in which vegetation is impractical, offering a complementary avenue to enhance workplace health and well-being.

In conclusion, this study contributes to the building science domain by offering an evidence-based, systematic approach to improve workplace health through NbS. The FDSS not only provides actionable insights for decision-makers but also establishes a foundation for future research into dynamic, data-driven strategies for sustainable workplace environments. Further studies should also focus on the interplay between living and nonliving biophilic elements, such as vegetation and fractal patterns, to create a more holistic understanding of their combined effects on workplace well-being. Owing to its flexibility, scalability, and ability to navigate uncertainty, the FDSS holds significant potential to transform workplace health interventions and inform policy development.

Supplementary Materials: The simulation code for implementing and assessing the impacts of Nature-based Solutions (NbS)—including an overview of its functionality, theoretical foundations,

practical applications, and execution guidelines for Google Colab—can be downloaded at: https://www.mdpi.com/article/10.3390/buildings15010117/s1.

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