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Integrating an Eco-Feedback Strategy to Enhance the Indoor Environmental Quality and Sleep Quality in Italian Bedrooms

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Abstract

This study examines the short-term impact of an "eco-feedback" strategy, based on an awareness-raising information campaign and an experimental campaign, on indoor environmental quality (IEQ) parameters and sleep quality in Italian bedrooms. Forty-one participants from Cassino, Italy, monitored the IEQ in their bedroom environments during the winter and spring seasons and assessed their sleep quality using the Groningen Sleep Quality Scale before and after receiving awareness-raising information. The experimental analysis revealed that, even if the IEQ and self-reported sleep quality before receiving the information were not representative of good sleep conditions (e.g., 94% of the volunteers slept in bedrooms with a median indoor CO_2 concentration >800 ppm, the equivalent continuous sound pressure level was always >30 dB, and the self-reported sleep quality conditions were characteristic of disrupted sleep or intermediate sleep disturbance), the subjects were not able to obtain significant changes in IEQ parameters after the information campaign and that, consequently, no noticeable changes in sleep quality were obtained as well. The limited effectiveness of the eco-feedback strategy adopted in this study can be attributed to the fact that the proposed approach only led to behavioral changes characterized by a limited effect on the indoor environmental quality. This was mostly due to the period under investigation: as an example, the low nighttime outdoor temperatures did not allow for an improvement in the building ventilation during the night.

Keywords: eco-feedback; CO_2; indoor environmental quality; Groningen sleep quality scale (GSQS); sleep quality

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Academic Editors: Igor Martek and Mehdi Amirkhani

Received: 29 May 2025
Revised: 23 June 2025
Accepted: 25 June 2025
Published: 27 June 2025

Citation: Solomon, M.T.; Canale, L.; Stabile, L.; D'Oliveira, A.; Andrade, A.; Buonanno, G. Integrating an Eco-Feedback Strategy to Enhance the Indoor Environmental Quality and Sleep Quality in Italian Bedrooms. *Buildings* **2025**, *15*, 2269. https://doi.org/10.3390/buildings15132269

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1. Introduction

People spend about 90% of their time indoors, with 69% of that time spent at home [1,2]. About 30% of indoor time is spent sleeping [3], accounting for one-third of a person's life [4], during which they inhale 27% of their daily air intake. Nonetheless, the air inhaled by people is often characterized by high concentrations of indoor-generated contaminants (e.g., CO_2) and pollutants since sleeping environments present low air exchange rates [5,6]; this phenomenon is even worse in cold periods when windows in bedroom environments are typically kept closed.

Sleep is essential for recovering from daily physical and mental fatigue, as well as for restoring the energy needed to support bodily functions [7,8]. Sleep quality is also crucial for maintaining high productivity during the day. Numerous studies have highlighted the impact of sleep quality on daytime alertness across various professions [5,9,10]. Regardless of age, indicators of good sleep quality include falling asleep quickly, experiencing fewer awakenings during the night, and spending less time awake after initially falling asleep. Sleep quality is indicated by four sleep continuity variables (sleep latency, awakenings over 5 min, wake after sleep onset, and sleep efficiency) and five sleep architecture variables (REM sleep, N1 sleep, N2 sleep, N3 sleep, and arousals) [11]. Sleep quality can be impacted by several factors, with one of the most crucial being the bedroom's indoor environmental quality (IEQ, i.e., temperature, relative humidity, noise, lighting) [12]. Indeed, each IEQ parameter has a distinct impact on the quality of sleep [13,14]. As an example, different studies [1,15–19] have demonstrated a significant decrease in sleep quality parameters with rising CO_2, temperature, and relative humidity levels both through subjective evaluations and physiological measurements. Similarly, noise significantly impacts sleep architecture and sleep quality [20–23]. Studies have demonstrated that nocturnal noise fragments sleep, leading to a redistribution of time spent in various sleep stages. Specifically, noise exposure typically increases the duration of wakefulness and stage 1 sleep while decreasing the time spent in slow-wave sleep and REM sleep, resulting in a shallower and less restorative sleep experience [20,24,25].

Although the occupants' behavior significantly influences the IEQ parameters while sleeping (e.g., affecting the ventilation of buildings, emitting pollutants through typical indoor combustion activities, etc.) [26,27], many people remain unaware of how their behavior affects their sleep environment [27,28]. For this reason, acting on behavioral change could improve the IEQ in bedroom environments. Among the different behavior change methods, "eco-feedback" strategies represent promising tools [29] as they can bridge the gap between a lack of awareness and an understanding of how behaviors affect the environment [30]. Eco-feedback was first defined by McCalley and Midden [31] as "information presented during the product-user interaction which prompts the user to adopt energy saving strategies". More generally, "eco-feedback" is a correcting strategy applied to different environmental contexts that helps modify specific behaviors, promoting habit modifications and, more broadly, supporting the transformation of a particular action into an automatic reflex (internalization) [32]. In particular, the eco-feedback strategy influences user behavior by providing real-time information on the investigated parameters (i.e., indoor air quality, occupancy, ventilation status, energy consumption, waste production) and delivering visual or auditory alerts based on sensor data. These alerts are designed to encourage actions (such as increasing ventilation, turning on air purifiers, or reducing pollutant-generating activities). The strategy is typically deployed by implementing low-cost sensors connected to a feedback interface (e.g., a display unit or mobile app). Different studies have demonstrated the effectiveness of eco-feedback approaches in reducing energy consumption as well as improving waste disposal [32–36]. Recently, we also applied, for the very first time, an eco-feedback strategy to indoor air quality issues [27]: indeed, we showed the short-term effectiveness of an eco-feedback strategy adopted to promote behavioral changes in the occupants with a view to reducing the concentration levels while airborne particle emitting sources were in operation in indoor environments.

In the present paper, we attempted to highlight how the occupants' behavior affects their sleep environment by evaluating the short-term effectiveness of an eco-feedback strategy with a view to enhancing indoor environmental quality and sleep quality in bedrooms. To this end, we (i) evaluated the baseline IEQ in the bedrooms and the sleep quality of 41 volunteers living in Central-southern Italy during the winter and spring seasons; then,

we (ii) applied an eco-feedback strategy, based on both a trustworthy information campaign and an experimental campaign, to evaluate, in the short term, the possible behavioral changes in the volunteers and their ability to improve the IEQ parameters and sleep quality. The experimental campaign was performed by adopting portable indoor environmental quality monitoring devices (to measure IEQ parameters in the bedroom environments) and a Groningen Sleep Quality Scale (GSQS) questionnaire (as a subjective measure of the sleep quality of the volunteers).

2. Materials and Methods

The eco-feedback strategy adopted in the present research is based on an information campaign and an experimental campaign. Its short-term effectiveness was evaluated through results gathered from IEQ and sleep quality measurements carried out before and after the information campaign, namely, during the "baseline" and "follow-up" periods.

2.1. Participants

The investigation was carried out from January 2024 to April 2024, i.e., in the winter and spring seasons, involving 41 volunteers (19 males and 22 females) living in Cassino (FR, Central-southern Italy). The volunteers' ages ranged from twenty to sixty-four years, with a median age of forty-nine. Thirty-three participants slept together (e.g., husband and wife, cohabiting couples) in a double-occupancy configuration, whereas the remaining eight slept alone (single occupancy). The participants confirmed this occupancy status throughout the daily monitoring process. The inclusion criteria considered volunteers who self-reported the absence of significant sleep or other critical health issues.

Of the 41 volunteers, only 34 (16 males and 18 females; 29 in double occupancy and 5 in single occupancy) were analyzed due to technical issues related to problems experienced with the indoor environmental quality monitors or because some of the volunteers were unable to continue the monitoring after the information campaign due to personal reasons. Consequently, thirty-four participants completed the IAQ monitoring both before and after the information campaign. Actually, twenty-eight participants were involved in the noise level measurements due to technical problems with the sound pressure measuring equipment. Information on the sex and age of the thirty-four participants who completed the IAQ monitoring both before and after the information campaign is reported in Table 1. Here, information regarding the room occupancy is also reported; the following occupancy conditions were recognized: some subjects shared a room, and both were involved in the study; other subjects shared a room, but just one of them was involved in the study; and finally, other subjects slept alone (single occupancy).

2.2. Procedure

In the baseline assessment, the IEQ parameters were monitored for two consecutive nights in the subjects' bedrooms during sleeping hours. Additionally, the participants completed a subjective assessment questionnaire (the Groningen Sleep Quality Scale) about their sleeping habits the morning after each monitoring night.

The results of the IEQ parameters and sleep quality in the baseline period were immediately processed and presented to the subjects during an information campaign provided by the researchers between the baseline and follow-up periods (i.e., the morning after the two-day baseline period). Recommendations and actions to enhance the sleeping environment were part of this feedback (provided along with a brochure) and are hereinafter described. Then, after the information campaign, the monitoring continued, starting from the same day for another two nights during the follow-up period. A scheme of the methodology adopted to evaluate the effectiveness of the eco-feedback strategy is shown in Figure 1.

Table 1. The sex and age of the thirty-four participants, type of occupancy of the bedroom, and information on the behavioral changes they adopted (if any) after the information campaign.

Subject	Sex	Age	Type of Occupancy	Behavioral Changes Adopted After the Information Campaign
1	M	57	Shared the bedroom with subject 2	Opened the bedroom window for a few minutes before going to sleep; no longer used the fireplace
2	F	56	Shared the bedroom with subject 1	Opened the bedroom window for a few minutes before going to sleep; no longer used the fireplace
3	F	62	Shared the bedroom with a subject not involved in the study	
4	F	53	Shared the bedroom with subject 5	
5	M	53	Shared the bedroom with subject 4	
8	F	46	Shared the bedroom with a subject not involved in the study	Opened the bedroom window for a few minutes before going to sleep and slept with the bedroom door open
9	F	48	Shared the bedroom with a subject not involved in the study	
10	F	64	Shared the bedroom with a subject not involved in the study	Opened the bedroom window for a few minutes before going to sleep and kept the kitchen window open while cooking
11	F	58	Shared the bedroom with a subject not involved in the study	Opened the bedroom window for a few minutes before going to sleep and slept with the bedroom door open
12	F	24	Single occupancy	Opened the bedroom window for a few minutes before going to sleep and slept with the bedroom door open
13	F	50	Shared the bedroom with a subject not involved in the study	Opened the bedroom window for a few minutes before going to sleep
14	F	48	Shared the bedroom with a subject not involved in the study	Opened the bedroom window for a few minutes before going to sleep and slept with the bedroom door open
17	M	39	Shared the bedroom with subject 18	Slept with the bedroom window open
18	F	26	Shared the bedroom with subject 17	Slept with the bedroom window open
19	F	25	Shared the bedroom with subject 20	Opened the bedroom window for a few minutes before going to sleep
20	F	20	Shared the bedroom with subject 19	Opened the bedroom window for a few minutes before going to sleep
21	M	50	Shared the bedroom with subject 22	Opened the bedroom window for a few minutes before going to sleep
22	F	46	Shared the bedroom with subject 21	Opened the bedroom window for a few minutes before going to sleep
23	M	54	Shared the bedroom with a subject not involved in the study	Opened the bedroom window for a few minutes before going to sleep and kept the kitchen window open while cooking
24	M	46	Shared the bedroom with a subject not involved in the study	
26	M	45	Single occupancy	Opened the bedroom window for a few minutes before going to sleep; turned down the volume of the radio
27	F	59	Shared the bedroom with subject 28	Slept with the bedroom door open
28	M	59	Shared the bedroom with subject 27	Slept with the bedroom door open
29	M	56	Shared the bedroom with a subject not involved in the study	Slept with the bedroom door open
30	M	43	Shared the bedroom with a subject not involved in the study	Opened the bedroom window for a few minutes before going to sleep
31	M	59	Single occupancy	

Table 1. *Cont.*

Subject	Sex	Age	Type of Occupancy	Behavioral Changes Adopted After the Information Campaign
32	M	32	Single occupancy	Opened the bedroom window for a few minutes before going to sleep
34	F	43	Shared the bedroom with subject 35	Opened the bedroom window for a few minutes before going to sleep and slept with the bedroom door open
35	M	50	Shared the bedroom with subject 34	Opened the bedroom window for a few minutes before going to sleep and slept with the bedroom door open
36	M	55	Shared the bedroom with a subject not involved in the study	
37	M	61	Shared the bedroom with a subject not involved in the study	
38	F	53	Shared the bedroom with a subject not involved in the study	Slept with the window of the adjacent bathroom open
40	F	45	Shared the bedroom with a subject not involved in the study	Opened the bedroom window for a few minutes before going to sleep
41	M	52	Single occupancy	Opened the bedroom window for a few minutes before going to sleep

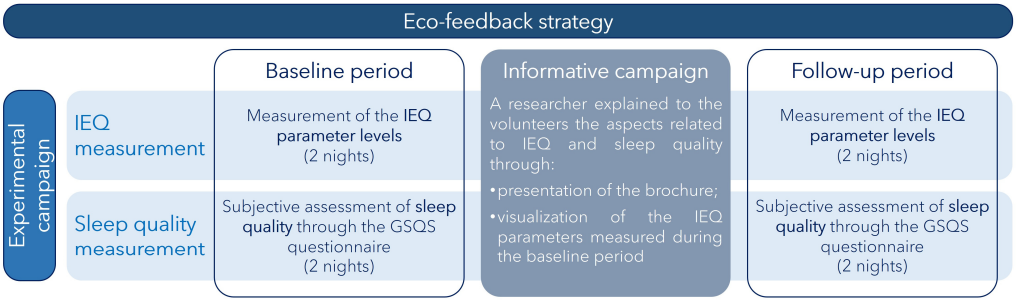


Figure 1. Scheme of the methodology adopted to evaluate the effectiveness of the eco-feedback strategy.

2.3. Objective Measurement of Indoor Environmental Quality

The IEQ parameters monitored during the two experimental campaigns were the temperature, relative humidity, CO_2 concentration, and sound pressure level. The temperature, relative humidity, and CO_2 concentration were measured through the wireless device Aranet4 HOME Sensor (Aranet, Riga, Latvia). The Aranet4 HOME is a handheld monitor equipped with an e-ink screen on the front, displaying real-time environmental readings. The device performs real-time monitoring and data storage without background light display or sound, ensuring no interference with the participants' sleep. The device presents the following resolutions: 1 ppm for CO_2 concentration, 0.1 °C for temperature, and 1% for relative humidity. The Aranet4 HOME was configured to measure at 1 min intervals during the experimental campaign.

The sound pressure level was measured through a PCE-SDL 1 sound meter data logger device (PCE Instruments, Manchester, UK). The device has a measuring range of 30 dB to 130 dB and an accuracy of $\pm$ 1.4 dB. The instrument was configured to the normal measuring mode, recording data in dBA units with a sampling rate of 2 s. This 2 s sampling rate was chosen to extend the storage capacity, allowing for continuous measurement over 3 days. The sound meter operates silently and without illumination, ensuring no disruption of the subjects' sleep. All the instruments adopted in the experimental campaign were recently calibrated by the manufacturers.

In order to monitor the IEQ parameters during sleeping time, the participants were instructed to place the two monitors (Aranet4 and PCE-SDL 1) in their bedroom at a fixed position relative to their heads. They were informed not to position the sensors near windows or any other ventilation devices to ensure the accurate measurement of the air quality parameters in the bedroom, without interference from ventilation through small gaps around the window.

To provide IEQ parameters characteristic of the two periods (baseline and follow-up periods), the median values and corresponding 5th–95th percentile ranges of the two nights (for each period) are provided for the temperature, relative humidity, and CO_2 concentrations. Differently, the sound pressure level value characteristic of the entire period is provided as the equivalent continuous sound pressure level (*LAeq*). In fact, the *LAeq* is a measure used in acoustics to represent the continuous equivalent level of fluctuating noise over a specified period. It provides a single value that reflects the varying sound levels as if they were a constant sound level over the same period. The *LAeq* was calculated based on the real-time sound pressure data measured by the instruments ($L_A(t)$) during the two nights as reported in Equation (1):

$$LAeq = 10log_{10}\left(\frac{1}{T}\int_0^T 10^{\frac{L_A(t)}{10}}dt\right) \quad (1)$$

Finally, the peak noise characteristic of the entire period was calculated as the average time spent at sound pressure levels > 45 dB between the two consecutive nights.

2.4. Subjective Assessment of Sleep Quality

The subjective evaluation of sleep quality is based on a self-monitored assessment using the Groningen Sleep Quality Scale questionnaire. This questionnaire was administered and recorded following each night of indoor environmental quality monitoring. The Groningen Sleep Quality Scale (GSQS) is a widely used tool for evaluating subjective sleep quality [37]. The scale ranges from 0 to 14 [37,38]; a score of 6 or above suggests disrupted sleep, while a score of between 0 and 2 indicates normal and refreshing sleep [39]. Finally, the score interval between normal and disturbed sleep is considered intermediate sleep disturbance [40]. The GSQS questionnaire was distributed through an online Google form. Additional questions about the time spent in the bedroom and the possible behavioral changes adopted after the information campaign were also added to the online form to properly process the IEQ data. The participants' responses were received, and the sleep quality was analyzed the next day after each night of indoor environmental quality monitoring in the bedroom.

2.5. Information Campaign and Eco-Feedback Strategy

The researchers organized a comprehensive information campaign for participants who had completed the initial objective measurement phase. As mentioned above, the results of the IEQ parameters and sleep quality in the baseline period were presented to the subjects during an information campaign provided by the researchers. Moreover, as part of this campaign, a detailed printed brochure was meticulously prepared. This brochure, the English translation of which is reported in Figure 2, was designed to provide a thorough explanation of several key topics: the concept and importance of the indoor environmental quality, the adverse effects of poor sleep quality, specific indoor environmental quality parameters along with their recommended ranges, and actionable measures to improve the IEQ. To ensure all participants were well-informed, the brochure was distributed alongside the results of objective measurements and self-reported sleep quality assessments collected during the baseline period. This approach ensured that participants not only received their personal data but also developed a deeper understanding of the broader context and significance of these measurements.

The recommended ranges of IEQ parameters were retrieved from guidelines and standards provided by different recognized institutions and agencies. Regarding CO_2, ASHRAE recommends that the indoor concentration should be no more than 700 ppm higher than that of the outdoor air. Thus, considering that the outdoor CO_2 concentration is usually around 400 ppm, indoor levels should ideally stay below 1100 ppm [41]. According to a study carried out by the Federation of European Heating, Ventilation, and Air Conditioning Associations (REHVA), an indoor environmental quality concentration of <800 ppm is considered reliable, with 1000 ppm marking the upper limit of acceptable indoor environmental quality. Based on these guidelines, in the brochure, we indicated 800 ppm as the limit for good bedroom environmental quality (reported in green in the brochure) and 1100 ppm as the limit for acceptable bedroom environmental quality (reported in yellow in the brochure); CO_2 concentrations > 1100 ppm were considered not acceptable for good sleep quality (reported in red in the brochure).

Regarding the temperature, the National Sleep Foundation (NSF) suggests that the optimal sleep temperature is slightly different for everyone; nonetheless, experts generally consider temperatures of >15 °C and <20 °C optimal for high-quality sleep. Baniassadi et al. [42] demonstrated that for elderly people, sleep was most efficient and restful when the nighttime ambient temperature ranged between 20 and 25 °C. Based on these guidelines, in the brochure, we indicated 20 °C as the limit for the optimal temperature range (reported in green) and 25 °C as an acceptable limit value (reported in yellow).



Figure 2. English translation of the illustrative brochure provided to the volunteers to inform them about the indoor environmental quality in bedrooms. As concerns the levels of IEQ parameters, values in green, yellow, and red are representative of good, acceptable, and not acceptable values for good sleep quality, respectively.

For relative humidity, it is generally recommended to keep the values indoors between 40% and 60% for comfort and health [43], as the majority of adverse health effects caused by relative humidity would be minimized by maintaining the indoor RH in this range [44]. Therefore, in the brochure, we indicated 40–60% as the optimal RH range (reported in green) and 30–40% and 60–70% as acceptable limit ranges (reported in yellow).

Finally, concerning the sound pressure level, to avoid sleep disturbance, the WHO recommends a limit value of 30 dB LAeq for continuous noise and 45 dB LAmax for single sound events [45]. Similarly, the EPA identified that a noise limit of 45 dB indoors prevents annoyance and activity interference, allowing sleep, recreation, work, and spoken conversation [46]. Based on these guidelines, we indicated 30 dB as the limit for optimal sleep quality (reported in green) and 45 dB (reported in yellow) as the limit for acceptable sleep quality.

Following the information campaign, the researchers conducted an additional two days of continuous monitoring (follow-up period): this extended monitoring period was crucial to evaluate any immediate changes in the indoor environmental quality produced by possible behavioral changes in the volunteers during their sleeping time.

Finally, the effectiveness of the eco-feedback provided through the information campaign was rigorously evaluated. This evaluation involved a detailed comparison of the indoor environmental quality parameters collected before and after the information campaign. By analyzing these data sets, the researchers aimed to determine the impact of the

information campaign on improving indoor environmental conditions and raising awareness among participants. To this end, at the end of the follow-up period, as mentioned above, the volunteers were also asked to complete a Google form reporting possible behavioral changes adopted after the information campaign. These behavioral changes are summarized in Table 1.

2.6. Statistical Analysis

For the statistical analysis, both Excel 2024 and Python 3.11 were used to investigate the impact of the adopted eco-feedback strategy. Specifically, the numpy, Pandas, matplotlib.pyplot, and SciPy. stats libraries were utilized within the Python script to conduct a comprehensive analysis. These Python-based analytical techniques were chosen for their flexibility, efficiency, and widespread acceptance in the scientific community. By leveraging the strengths of Python's data analysis ecosystem, we conducted a thorough and rigorous statistical analysis of the collected data.

In order to perform a statistical analysis with a view to observing the variation in the environmental quality and sleep quality parameters during the eco-feedback strategy, a preliminary normality test (Shapiro–Wilk test) was performed to check the statistical distribution of the data. Since the data did not meet a Gaussian distribution, a non-parametric test was considered in the analysis. In particular, we employed the Wilcoxon and Mann–Whitney U signed-rank test, a non-parametric statistical test suitable for paired data, adopting a 95% confidence level (i.e., p-value < 0.05). This test was applied to compare the measurements of CO_2, RH, temperature, sound pressure level, peak noise, and sleep quality before and after the information campaign. By analyzing paired samples, this test enabled us to account for the natural variations within individual subjects, providing a more accurate assessment of the information campaign's effect. The Wilcoxon signed-rank test examines information on the differences and the magnitude of difference between the two studied parameters (baseline and follow-up periods); it is the most powerful "sign test" [47], and it is very appropriate for a repeated-measure design where the same subjects are evaluated under two different conditions [48].

3. Results

3.1. Indoor Environmental Quality Parameters and Sleep Quality of the Subjects

In Table 2, the results of environmental quality parameter measurements in the subjects' bedrooms during the experimental campaigns carried out in the baseline and follow-up periods are reported. The CO_2, RH, and temperature values reported here for each period represent the median and 5th–95th percentile ranges of the two nights (please note that for both periods the experimental campaign was conducted for two consecutive nights). Similarly, the sound pressure level values represent the average equivalent continuous sound pressure level (LAeq) of the two consecutive nights, and the peak noise values represent the average time spent at sound pressure levels > 45 dB between the two consecutive nights. The data reported in Table 2 were calculated on the basis of the actual bedtime and wake-up time of the volunteers investigated; thus, the values can be different for people sharing a bedroom.

As concerns the relative humidity, 50% of the volunteers in the baseline period and 56% in the follow-up period experienced median values > 60%, but just 3% of them slept with a median RH > 70%. The median temperature in the bedrooms was >20 °C for 32% and 35% of the volunteers during the baseline and follow-up periods, respectively. No median values > 25 °C were recorded. Both the temperature and relative humidity remained quite constant during the night, as shown by the 5th–95th percentile ranges reported in the table for each subject.

Table 2. Indoor environmental quality parameters measured in bedrooms before (baseline period) and after (follow-up period) the information campaign for each participant in the study. Sleep quality results measured through the Groningen Sleep Quality Scale questionnaire are also reported.

Subject	CO_2 (ppm)		Relative Humidity (%)		Temperature (°C)		Sound Pressure Level, LAeq (dBA)		Peak Noise, Time at >45 dB (s)		Sleep Quality	
	Baseline	Follow-Up	Baseline	Follow-Up	Baseline	Follow-Up	Baseline	Follow-Up	Baseline	Follow-Up	Baseline	Follow-Up
1	1075 (916–1144)	1085 (901–1217)	58 (55–60)	62 (58–64)	19.6 (18.7–20.7)	20.2 (19.8–20.8)	39.5	40.6	203	1036	9	6
2	1075 (916–1144)	1089 (922–1217)	58 (55–60)	62 (59–64)	19.6 (18.7–20.7)	20.2 (19.8–20.7)	39.5	40.6	203	1036	1	1.5
3	1032 (725–1829)	844 (726–1228)	61 (59–66)	63 (58–64)	18.3 (17.4–19.9)	19 (18.5–19.9)					5.5	3
4	2460 (1489–2856)	1919 (1384–2321)	64 (60–66)	63 (59–64)	18.0 (17.5–18.9)	18.7 (18.1–19.4)					1	0.5
5	2469 (1684–2877)	1922.5 (1331–2323)	64 (60–66)	63 (60–64)	17.9 (17.5–19.2)	18.7 (18.1–19.4)					2	1.5
8	2001 (1845–2055)	1941 (1526–2006)	55 (53–56)	57 (54–57)	20.4 (20–20.6)	20.3 (20–20.5)	33.0	35.0	166	85	6.5	0
9	2731 (2206–3320)	1853 (1691–1986)	69 (67–73)	72 (71–72)	15.8 (15–16.5)	15.5 (14.9–17.1)	40.5	39.8	218	88	2.5	5.5
10	1246 (1044–1541)	1239 (1095–1471)	54 (53–56)	56 (54–57)	19.1 (18.2–20.2)	19.2 (18.4–20.2)					0.5	0
11	1404 (1123–1474)	1341 (997–1457)	60 (58–62)	61 (59–63)	16.9 (16.4–18.3)	17.4 (16.9–18.6)					4.5	1
12	1086 (791–1152)	968 (828–1390)	58 (57–61)	51 (50–53)	18 (17.2–18.9)	19.3 (18.2–21)	37.4	36.1	73	69	7	5
13	1603 (1350–1690)	1633 (1158–1920)	63 (62–65)	64 (60–65)	20.5 (20.1–20.8)	18.9 (18.2–20.0)					6	3
14	942 (688–1091)	999 (653–1192)	54 (52–56)	52 (48–55)	20.8 (20.4–21.5)	20.8 (20.4–21.6)	38.0	37.7	246	25	1.5	2
17	1866 (1179–2369)	904 (763–1033)	61 (54–65)	56 (51–57)	16.4 (15.9–17.05)	17.9 (17.5–18.8)	31.7	32.7	471	555	1	8
18	1833 (785–2341)	885 (796–1053)	61 (52–65)	55 (47–57)	16.6 (15.9–17.4)	18.1 (17.5–20.5)	32.9	33.8	1060	770	0	0
19	1397 (1194–1561)	1477 (1394–1585)	62 (60–64)	63 (61–64)	18.5 (18.3–19.1)	19 (18.8–19.4)	38.1	38.1	7	14	6	3.5
20	1365 (1108–1558)	1450 (1241–1561)	62 (60–64)	63 (59–64)	18.6 (18.2–19.3)	19.1 (18.8–19.7)	38.3	38.0	63	9	3.5	8
21	2496 (1240–3305)	2402 (1387–3160)	63 (58–65)	57 (53–59)	19.9 (19.8–20.3)	19.7 (19.6–19.8)	39.5	39.7	493	442	4.5	3
22	2526 (1250–3333)	2408 (1432–3189)	63 (58–65)	57 (53–59)	19.9 (19.8–20.3)	19.7 (19.6–19.8)	39.4	39.7	504	441	8.5	7
23	2262 (2045–2420)	1640 (1398–1880)	72 (71–75)	68 (66–71)	18.9 (18.6–19)	18.4 (18.4–18.9)	33.1	33.5	378	379	1.5	2
24	2043 (1386–2471)	1900 (1234–2502)	67 (64–70)	69 (67–71)	17.9 (17.4–19.2)	17.1 (16.6–17.8)	41.6	41.9	2831	3117	12	14

Table 2. *Cont.*

Subject	CO_2 (ppm)		Relative Humidity (%)		Temperature (°C)		Sound Pressure Level, LAeq (dBA)		Peak Noise, Time at >45 dB (s)		Sleep Quality	
	Baseline	Follow-Up	Baseline	Follow-Up	Baseline	Follow-Up	Baseline	Follow-Up	Baseline	Follow-Up	Baseline	Follow-Up
26	1127 (842–1456)	980 (683–1314)	57 (54–59)	54 (49–55)	20.7 (19.88–21.2)	20.5 (19.8–21)	47.7	40.0	2566	593	5	10
27	1110 (691–1288)	1094 (628–1332)	61 (53–62)	63 (57–63)	19.2 (19–19.3)	19.0 (18.6–19.3)	39.7	40.4	130	166	11	2.5
28	1165 (847–1468)	1130 (850–1458)	57.5 (53–61)	62 (57–63)	19.2 (18.9–19.3)	18.9 (18.6–19.2)	45.3	46.5	2421	3904	1.5	2
29	1237 (956–2227)	1434 (964–1785)	59.5 (54–64)	61 (60–62)	18.9 (18.7–18.9)	18.4 (18.4–18.6)	33.7	47.6	38	1009	3	1
30	918 (785–981)	974 (871–1083)	55 (54–56)	55 (54–61)	21.1 (19.52–21.5)	20.1 (19.08–20.5)	40.1	40.4	448	260	0	0
31	795 (707–834)	857 (835–876)	60 (59–61)	58 (58–58)	19.8 (19.3–20.1)	18.2 (17.9–18.8)	50.4	50.6	3385	3640	6	8
32	1480 (856–1904)	1391 (758–1706)	61 (57–66)	60 (58–61)	22.0 (21.8–22.3)	21.6 (21.3–21.6)	42.0	41.6	461	180	1.5	7
34	2135 (1568–2463)	2056 (1387–2618)	57 (56–59)	64 (61–64)	18.9 (18.7–19.2)	19.7 (19.5–20.1)	38.9	38.9	80	118	9	3.5
35	2206 (1612–2481)	2078 (1733–2575)	57 (56–59)	64 (62–64)	19.0 (18.7–19.2)	19.7 (19.6–20.1)	38.9	38.2	80	7	6.5	8.5
36	899 (806–993)	1274 (864–1469)	58 (55–59)	64 (61–66)	21.4 (20.6–21.5)	20.6 (20.4–20.7)	38.6	38.8	98	73.5	2	1.5
37	909 (482–1115)	1133 (864–1273)	53 (49–56)	60 (59–61)	21.4 (20.8–21.8)	21.1 (20.5–21.3)	43.9	37.3	2390	518	1.5	7.5
38	886 (670–1104)	776 (492–850)	58 (56–65)	55 (54–56)	21.4 (21.2–21.6)	21.7 (21.5–21.8)	44.8	50.7	3025	967	1	0
40	975 (785–1298)	952 (788–1046)	62 (60–63)	61 (59–62)	20.7 (20.5–20.8)	21.5 (21.4–21.6)	45.7	43.7	1905	846	1	1
41	747 (585–971)	767 (725–802)	61 (59–65)	56 (53–56)	23.7 (23.4–23.9)	23.2 (23.1–23.2)	46.6	40.0	5647	418	3	5

The other monitored parameters mostly did not fall within the ranges indicated as representative of good sleep conditions. Indeed, both in the baseline and follow-up periods, 94% of the volunteers slept in bedrooms with a median indoor CO_2 concentration > 800 ppm. Actually, 65% of the volunteers in the baseline period and 59% in the follow-up period experienced a CO_2 concentration that was not even acceptable on the basis of the ranges indicated in the brochure, as the median concentrations were >1100 ppm. The median CO_2 concentrations were even >2000 ppm with peaks (95th percentile values in the table) higher than 3000 ppm. In fact, different from the temperature and relative humidity values, the CO_2 concentration increases significantly during the night due to the continuous emission of the occupants while sleeping and the low ventilation rates observable when windows are closed. This is clearly highlighted in Figure 3 where, as an illustrative example, the CO_2 concentration trends measured in the bedroom occupied by subjects 17 and 18 during the baseline and follow-up periods are reported: here, it is clearly shown that, during the baseline period, the presence of the subjects and the reduced ventilation (windows were kept closed) led to a CO_2 concentration higher than 2000 ppm.

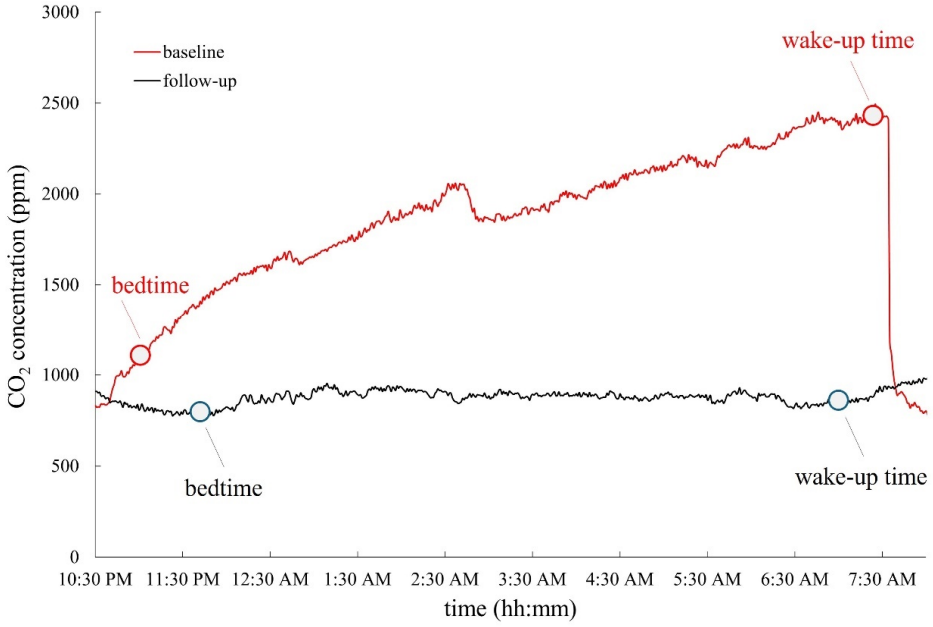


Figure 3. CO_2 concentration trends measured in the bedroom occupied by subjects 17 and 18 during the baseline and follow-up periods (on one of the two consecutive measurement nights); bedtime and wake-up time of subject 17 are also indicated.

The equivalent continuous sound pressure level (LAeq) experienced by the volunteers was always >30 dB both in the baseline and follow-up periods; moreover, 18% and 14% of them slept with an LAeq > 45 dB during the baseline and follow-up periods, respectively. As concerns the peak noise events, 68% of the volunteers were exposed to sound pressure levels > 45 dB for more than 10 min during both measurement periods. Some of them were exposed to very long peak noise (even >1 h); in fact, 29% and 11% of the volunteers slept at >45 dB for at least half an hour during the baseline and follow-up periods, respectively. An illustrative example of exposure to high sound pressure levels is reported in Figure 4, where the sound pressure level trends measured in subject 26's bedroom during the baseline and follow-up periods are reported as 1 min average values: the baseline trend highlights sound pressure level peaks (in particular during the first hours of sleep), as he habitually slept with a radio on throughout the entire night.

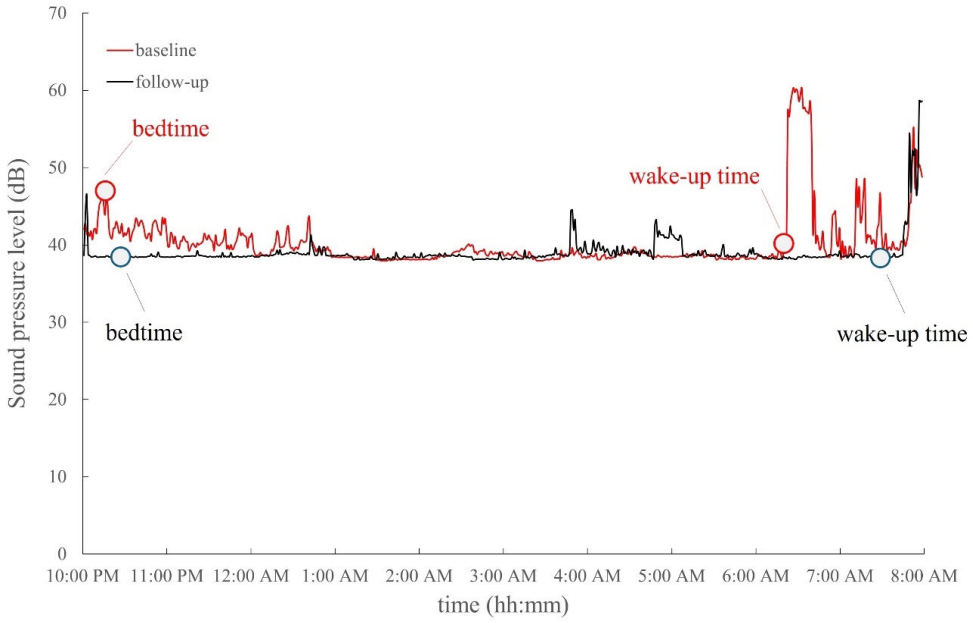


Figure 4. Sound pressure level trends measured in subject 26's bedroom during the baseline and follow-up periods (on one of the two consecutive measurement nights); bedtime and wake-up time are also indicated.

In Table 2, sleep quality results obtained through the self-administered Groningen Sleep Quality Scale questionnaire are also reported. In particular, the average GSQS scores of the two consecutive nights analyzed during the baseline and follow-up periods are reported. The data show that only 38% and 35% of the volunteers during the baseline and follow-up periods, respectively, presented a score < 2, which is characteristic of normal and refreshing sleep, whereas the corresponding percentages of disrupted sleep (score > 6) were 24% and 26%, respectively. Thus, most volunteers presented scores ranging from 2 to 6 during both periods, representing intermediate sleep disturbance [40].

To summarize, the data reported in Table 2 showed no particular differences in the IEQ parameters and sleep quality scores during the baseline and follow-up periods. A detailed analysis of these differences is reported hereinafter.

3.2. Eco-Feedback Effectiveness

After the information campaign, the volunteers tried to improve the IEQ in their bedrooms based on the suggestions provided by the researchers. Nonetheless, as a result of the information provided via the Google form at the end of the follow-up period, the behavioral changes adopted by the volunteers (if any) during the follow-up period (summarized in Table 1) were quite limited. The volunteers mostly tried to increase the ventilation in their bedrooms by just opening the windows before going to bed. More intense room ventilation (e.g., sleeping with windows open) was hardly feasible in the winter and spring due to the low outdoor temperature during the night (the average nighttime temperature during the investigated period ranged from 7 to 15 °C, as retrieved from the weather station available at the University of Cassino and Southern Lazio). Indeed, just two subjects (a couple, subjects 17 and 18) slept with the window of their bedroom open all night long during the follow-up period. This is highlighted by the CO_2 trend of the follow-up period for subject 17 reported in Figure 3: he increased the ventilation significantly, and the CO_2 concentration remained under 1000 ppm for the entire night. As mentioned above, other subjects (please see Table 1) tried to improve the ventilation by opening the bedroom window for a few minutes before going to sleep. Nonetheless, this approach only led to a minimum reduction (if any) in the CO_2 concentration, as shown by the median values reported in Table 2.

As concerns the exposure to high sound pressure levels, a behavioral change was implemented only by subject 26: indeed, as mentioned above, he habitually left a radio on all night; nonetheless, after the information campaign, he turned down the volume of the radio during the follow-up period. This is highlighted by the sound pressure level trends measured in subject 26's bedroom during the follow-up period reported in Figure 4, where the noise peaks are limited with respect to the baseline trend. Other volunteers were not able to reduce the sound pressure levels during the night since their background value was >30 dB.

In order to assess the effectiveness of the eco-feedback strategy in improving the IEQ parameters, the paired differences in the values measured in the follow-up period with respect to the baseline period were calculated and are reported as box plots in Figure 5. Moreover, the statistical analysis results of such differences (i.e., *p*-values), obtained by applying the Wilcoxon signed-rank test, are also shown.

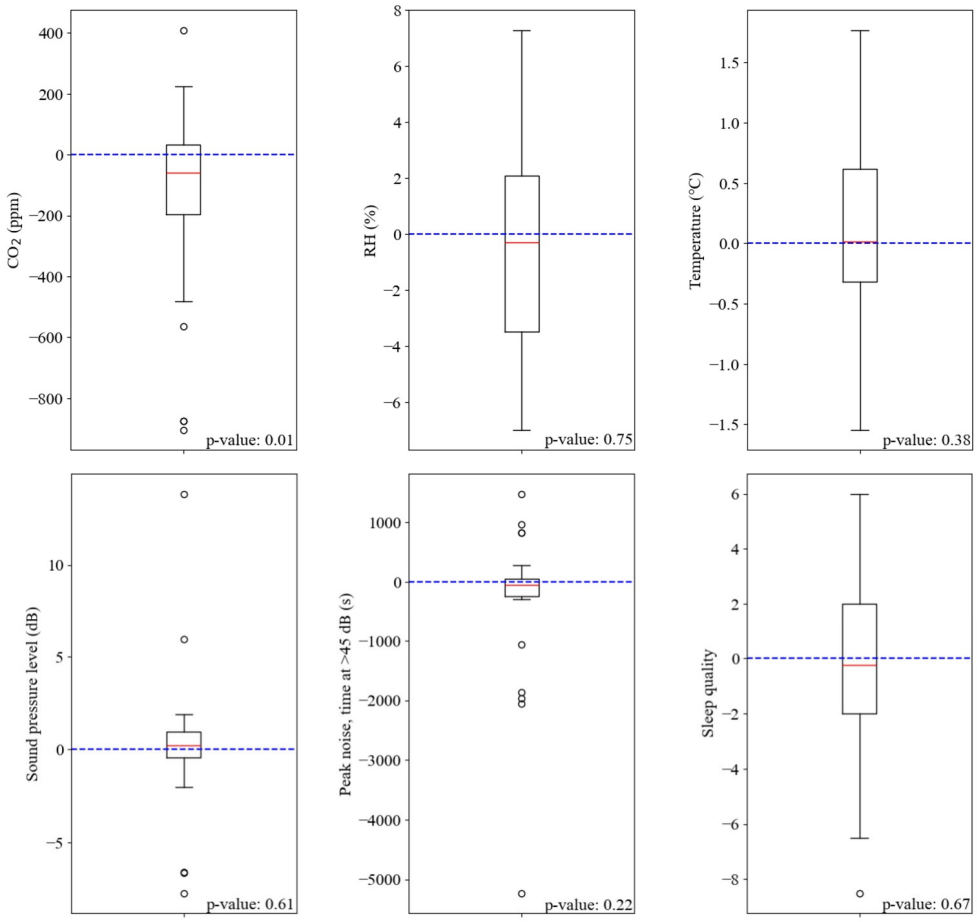


Figure 5. Box plots of the paired differences in IEQ parameters and sleep quality scores measured in the follow-up period with respect to the baseline period.

The CO_2 data amongst the follow-up and baseline periods were statistically different (*p*-value of 0.01); indeed, a median reduction of about 60 ppm was detected in the follow-up period. This reduction is minimal and within the typical uncertainty of the CO_2 monitors [6,49]; in other words, we can consider the subjects' exposure to CO_2 to be similar in the two periods. We also analyzed the exposure of males and females to CO_2 separately and recognized that females presented a statistically significant reduction ($p = 0.03$) in the exposure to CO_2, whereas for males, the reduction was not statistically significant ($p = 0.17$). Considering that most of the volunteers were couples and slept together, the reason for such an improvement in terms of the CO_2 exposure of the females is likely due to a behavioral

change adopted after the information campaign. In particular, we observed that, in most cases, women tend to go to their bedrooms earlier. They often leave the window open until they arrive in the room, which exposes them to lower CO_2 concentrations. However, when the males enter the bedroom later, the CO_2 levels are already elevated due to their partner's presence and reduced ventilation. As a result, males are generally exposed to higher CO_2 concentrations compared to females. Nonetheless, such a reduction in the exposure to CO_2 for females is still well within the typical uncertainty of the CO_2 monitors [6,49]; thus, once again, we can consider the subjects' exposure to CO_2 to be similar in the two periods, both for males and females. The authors point out that a limited CO_2 concentration reduction is not expected to provide a significant improvement in terms of sleep quality; in fact, Buonanno et al. [17], in their study aimed at experimentally determining the effect of the bedroom environment on sleep and physiological parameters, recognized that a reduction of 100 ppm in the CO_2 concentration provides just a negligible improvement in terms of sleep quality.

The limited effect of eco-feedback on the CO_2 concentration is linked to the need to maintain specific thermo-hygrometric conditions. Indeed, ventilation in bedrooms is difficult to enhance during the winter and spring seasons. Consequently, the behavioral changes adopted by the volunteers did not modify the thermo-hygrometric conditions of the bedrooms. Indeed, the median values of relative humidity and temperature measured in the baseline and follow-up periods were not statistically different (p-values > 0.05). Therefore, most subjects could not significantly improve the building ventilation during the nighttime; more intense manual airing would have likely caused higher differences in the thermo-hygrometric conditions (e.g., a temperature reduction during the follow-up period).

Also, for continuous and peak noise levels, no statistical differences were recognized in the follow-up periods with respect to the baseline ones. Indeed, despite some critical behaviors (e.g., subjects listening to the radio during the night), most people could not further improve their exposure to high sound pressure levels. Please consider that, once again, applying manual airing strategies would have likely worsened the exposure to high sound pressure levels due to noises coming from outdoors.

To assess the effectiveness of the eco-feedback strategy in improving the (self-monitored) sleep quality, the paired differences in the sleep quality scores measured in the follow-up period (through the GSQS questionnaire) with respect to the baseline period are reported, as box plots, in Figure 5 along with the statistical analysis results (i.e., p-values) obtained through the Wilcoxon signed-rank test. The analysis revealed no statistically significant differences in sleep quality perception after the information campaign (i.e., $p = 0.67$), with most volunteers reporting disrupted sleep or intermediate sleep disturbance (as shown in Table 2). In other words, a worsening of the sleep quality during the follow-up period was also reported by a few of the volunteers, even when their exposure to the IEQ parameters improved: this is likely due to the fact that other parameters beyond the IEQ can affect the sleep quality [7,50].

3.3. Significance and Limitations

To the best of our knowledge, this is the first study attempting to apply an eco-feedback strategy to enhance the indoor environmental quality in bedrooms and people's related sleep quality. The analysis revealed that, in general, the applied eco-feedback strategy, based on the trustworthy information campaign and the experimental campaign, is not able to improve the bedroom environmental quality and the sleep quality in the short term during cold seasons. Indeed, the study revealed a lack of significant differences in the sleep quality of the subjects investigated, which can be attributed to the absence of notable changes in the IEQ following the information campaign. The eco-feedback strategy is generally

meant to improve the subjects' awareness with a view to modifying specific behaviors and promoting habit modifications [32]. Nonetheless, in this study, a possible improvement in the subjects' awareness (concerning the IEQ in their bedrooms and their sleep quality) did not correspond to a successful sleep habit modification. This cannot be considered an inadequacy of the information campaigns per se, but it is due to the limited alternatives available to individuals to improve the environmental quality parameters while sleeping. As an example, an improvement in the exposure to CO_2 would have required ventilation rates that could only be reached by leaving the windows open all night long (which is not suitable in cold periods and could negatively affect the temperature and relative humidity levels) or installing mechanical ventilation systems able to guarantee the desired ventilation rates. Similarly, as concerns exposure to high sound pressure levels, further improvement can hardly be obtained; indeed, all the subjects investigated here were exposed to sound pressure levels >30 dB both before and after the information campaign; thus, improving this condition would have required very unfeasible solutions, e.g., soundproofing the walls of the bedrooms.

It would be interesting to evaluate, in future studies, the effectiveness of the eco-feedback strategy in warmer seasons; indeed, in that case, the ventilation of the bedroom could be easily performed by sleeping with the windows open, and this would reduce the subjects' exposure to CO_2. Nonetheless, this could result in a simultaneous worsening of the sound pressure levels due to the possible noises produced outdoors. Moreover, in warmer seasons, a negative effect on sleep quality could also occur due to higher temperatures and relative humidity levels.

Despite the novelty of this paper, some limitations should also be mentioned: The first aspect to consider is the sample size and representativeness. Indeed, the study analyzed a relatively small sample, which may pose a problem regarding the generalization of the findings. A further limitation is related to the fact that we only investigated the short-term effectiveness of the eco-feedback strategy; nonetheless, the durability of the behavior-changing effect is a critical aspect of eco-feedback approaches. Therefore, future studies should consider a larger sample population as well as the long-lasting effect of the eco-feedback strategy. This is not an easy task, since it would require very expensive and time-demanding experimental campaigns.

Another limitation pertains to the measurement method utilized in this study to measure the sleep quality of the subjects; indeed, we adopted a self-administered questionnaire (Groningen Sleep Quality Scale), which could be affected by individual perceptions and biases. Future assessments should consider more-objective methods of measuring sleep quality, e.g., adopting wrist actigraphs [17].

Finally, future studies should also take into account health history, medication use, sleep disorders, anxiety levels, and exercise habits, as these factors can enhance analyses by sample strata and provide a clearer explanation of potential differences in sleep influenced by eco-feedback [7,50].

4. Conclusions

This study represents the first attempt to apply an eco-feedback strategy to improve the indoor environmental quality in bedrooms and individuals' sleep quality. In particular, this study examines the short-term impact of the "eco-feedback" strategy, and its results pertain to the winter and spring periods in Central Italy.

The experimental analysis in the baseline period revealed that the environmental quality parameters mostly did not fall within the ranges indicated as representative of good sleep conditions (e.g., 94% of the volunteers slept in bedrooms with a median indoor CO_2 concentration > 800 ppm, and the equivalent continuous sound pressure level was always

>30 dB), and the self-reported sleep quality conditions were characteristic of disrupted sleep or intermediate sleep disturbance (i.e., GSQS scores ranging from 2 to 6). Although the information campaign increased the participants' awareness regarding the environmental conditions of their bedrooms, the behavioral changes implemented were limited and did not result in significant short-term improvements in the environmental conditions or sleep quality. Indeed, the CO_2 concentrations, temperature, relative humidity, sound pressure levels, and peak noise remained statistically similar before and after the information campaign, as did the self-reported sleep quality scores (p-values resulting from the Wilcoxon and Mann–Whitney U signed-rank test were >0.01, or the differences were lower than the uncertainty of the instrumentation). Therefore, the boundary conditions typical of the place and period of the study (e.g., nighttime outdoor temperature) did not allow the individuals to improve the environmental quality parameters while sleeping.

The study highlights the importance of implementing longer-term interventions encompassing warmer seasons and incorporating more-objective sleep quality measures. This approach is essential to comprehensively evaluate the effects of environmental improvements on sleep. Consequently, further research is needed to refine eco-feedback strategies and ensure lasting enhancements in indoor environmental quality and sleep quality.

Author Contributions: Conceptualization, G.B. and A.A.; methodology, L.S., L.C. and A.D.; software, M.T.S.; validation, L.S. and L.C.; formal analysis, M.T.S. and A.D.; investigation, M.T.S.; resources, G.B.; data curation, M.T.S. and A.D.; writing—original draft preparation, M.T.S. and L.S.; writing—review and editing, G.B.; visualization, M.T.S.; supervision, G.B. and A.A.; project administration, G.B.; funding acquisition, G.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Acknowledgments: The authors thank the 41 volunteers involved in the experimental campaign for their availability.

Conflicts of Interest: The authors declare no conflicts of interest.

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