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# The impact of built environment engineering on healthcare-associated infection rates: A cross-sectional analysis of ventilation, materials, and layout

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## Abstract

Addressing the ongoing worldwide problem of healthcare-associated infections (HAIs) requires looking beyond the microbiological interventions to the role of the built environment. This cross-sectional study conducted in a 750-bed tertiary hospital quantitatively assessed the integrated effects of three engineering controls (ventilation, surface materials and spatial layout) on HAI rates over 12 months. Data on air changes per hour (ACH), surface bioburden, room occupancy and flow of footfall patterns were correlated with laboratory confirmed HAIs on four wards. Results showed that ACH was a strong predictor of lower infection rates and each unit increase in ACH was associated with a 17.3 percent reduction in infection. Surface porosity directly contributed to bacterial colonization, which was associated with an 11% increase in contact-transmitted HAIs per 5 CFU/cm2 increased, whereas single-occupancy rooms had 42% fewer HAI rates than multi-bed rooms. A multivariate model combining these factors accounted for 78% variance of HAIs. These results show that strategic, integrated design interventions in ventilation, material choice, and layout are important in mitigating the transmission of infection and improving patient safety, with the need to address hospital design as a first line of infection control.

**Keywords:** *health, healthcare, surface materials, hospital design*

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## 1. Introduction

Healthcare-associated infections (HAIs) are a critical global health burden, causing prolonged hospitalization, increased costs, and greater patient morbidity and mortality (Patil et al., 2025). The World Health Organization (WHO) estimates that out of every 100 hospitalized patients, 7 in developed countries and 15 in developing countries acquire at least one HAI, affecting millions of patients annually and creating a substantial economic burden on healthcare systems (Varghese, 2025). While the proper implementation of stringent hygiene practices and antimicrobial stewardship is an integral part of any infection control plan, the continued prevalence of HAIs demonstrates the limitations of these interventions and indicates the insufficiency of purely microbiological and behavioral approaches in achieving comprehensive infection control (Kim et al., 2025; Varghese, 2025). The emergence of multidrug-resistant organisms (MDROs) further complicates this landscape and reduces the effectiveness of antimicrobial treatments, increasing the urgency for robust, non-pharmacological prevention strategies.

An emerging body of evidence identifies the built environment as a critical determinant in the chain of infection transmission (Jones et al., 2025). Although the concept of "Prevention through Environmental Design" (PtD) has long been established in other safety-critical industries, it is now gaining significant traction in healthcare as a systematic approach to reducing infection risks through proactive architectural and engineering solutions. The design and engineering of hospital infrastructure, such as ventilation systems, surface materials, and spatial layouts, can either facilitate or impede pathogen transmission. This has led to growing recognition that civil and environmental engineering principles must be integrated into healthcare design to effectively address the risk of HAIs (Barbati et al., 2026).

The COVID-19 pandemic served as a stark reminder of the critical role the environment plays in disease transmission, particularly the role of ventilation systems in controlling the spread of airborne pathogens (Lishchynskyi et al., 2022). This recent global experience has spurred increased research into engineering controls; however, a fragmented approach persists in both research and practice. Existing studies are often confined within disciplinary silos: engineering literature emphasizes airflow dynamics, architectural research focuses on spatial configurations, and clinical studies prioritize surface decontamination protocols (Stinson et al., 2025). This fragmentation limits the ability of healthcare administrators to make informed decisions on how to allocate limited resources for maximum impact on infection prevention (Barbati et al., 2026; Poelmans & Heerden, 2026).

A significant gap therefore exists in interdisciplinary research that simultaneously analyzes these factors within a unified framework to directly quantify their collective impact on HAI rates. This study seeks to address this gap by providing a holistic analysis of the role of the built environment. Specifically, it focuses on three critical engineering controls: (1) ventilation systems, which influence air quality and airborne pathogen dispersion; (2) material selection, which affects microbial adhesion and survival; and (3) floor plan layout, which influences workflow and cross-contamination risks. By integrating quantitative data across these three domains, this research moves beyond theoretical discussion and provides actionable evidence for healthcare facility design and retrofitting. The primary objective is to quantitatively assess the correlation between these engineering controls and the incidence of nosocomial infections in order to generate evidence-based recommendations. Ultimately, this study demonstrates that strategic, integrated structural interventions are not merely supportive measures but active and powerful components of the infection control arsenal, capable of significantly reducing the burden of HAIs by addressing modifiable environmental factors (Zeng et al., 2025).

## 2. Literature Review

The role of the hospital built environment in infection transmission has received increasing attention in scholarly publications, shifting away from the traditional focus on microbiology and hygiene protocols. This review synthesizes current knowledge on the three primary structural elements under investigation, ventilation, materials, and layout, and extends into closely related areas to establish a comprehensive foundation for this study’s integrated analysis.

### *2.1. Ventilation Systems and Infection Control*

Mechanical ventilation is an important engineering control for maintaining indoor air quality. Standards such as ASHRAE 170 specify minimum requirements for Air Changes per Hour (ACH) (Jones et al., 2025; Stinson et al., 2025), with higher requirements depending on the type of protective environment and isolation room. The directionality of airflow, sustained by pressure differentials, is also critical for the containment of infectious agents. Furthermore, the incorporation of High-Efficiency Particulate Air (HEPA) filtration has been shown to significantly reduce airborne particulates, thereby decreasing the risk of invasive aspergillosis and other nosocomial infections (Au et al., 2010). Inadequate ventilation has been directly correlated with outbreaks of airborne illnesses, highlighting its fundamental role in infection prevention (Au et al., 2010; Jones et al., 2025).

The COVID-19 has fundamentally reshaped understanding of airborne disease transmission, placing ventilation at the forefront of infection control discussions. Recent research has established that the spread of SARS-CoV-2 occurs primarily through airborne aerosols in indoor environments, making effective ventilation paramount in reducing outbreak risks (Khan & Malik, 2022; Lishchynskyi et al., 2022; Prosun et al., 2026). This has stimulated innovation in air treatment technologies, with a systematic review conducted by Jones et al. (2025) validating the efficacy of portable HEPA filters in reducing airborne microbial counts in clinical spaces, thereby providing a flexible solution for retrofitting older infrastructure.

### *2.2. Surface Materials and the Colonization of Microorganisms*

The porosity of surface materials and their ease of cleaning directly affect their role as pathogen reservoirs. Non-porous, seamless materials are easier to disinfect and less likely to harbor biofilms than porous materials (Lishchynskyi et al., 2022). This has prompted research into “self-disinfecting” surfaces, with copper and its alloys demonstrating strong intrinsic antimicrobial properties and a significant reduction in surface bioburden (Khan & Malik, 2022). The efficacy of cleaning protocols is intrinsically linked to material selection. Damaged or stained surfaces may harbor pathogens even after cleaning has been completed, thereby compromising the effectiveness of the protocol. Thus, material selection is a fundamental component of an infection control strategy rather than merely an aesthetic consideration.

Research into advanced materials continues to evolve. Beyond copper, surfaces coated with titanium dioxide ($TiO_2$), which exhibit photocatalytic antimicrobial properties activated by light exposure, have shown potential in reducing the viability of pathogens such as MRSA and VRE in laboratory settings (Orakzai, 2021). However, their efficacy has varied in real-world clinical trials, suggesting that factors such as lighting conditions and organic soiling may influence performance (Melo-Soares et al., 2025). The long-term durability and economic advantages of these advanced materials compared to conventional surfaces requiring regular cleaning remain critical areas for health economic analysis (Khan, 2024).

### *2.3. Spatial Arrangement and Workflow Design*

Architectural layout determines patterns of movement among patients, staff, and visitors and directly influences cross-contamination risks. A major design consideration is the comparison between multi-bed bays and single-room occupancy. Evidence strongly suggests that single rooms reduce transmission risks by enabling source isolation and simplifying cleaning procedures (Bayraktar Sari & Jabi, 2024). Regardless of room type, the strategic placement of hand hygiene stations, ensuring immediate availability at the point of care, is a key determinant of compliance (Khan et al., 2026). The concept of "acuity-adaptable" rooms, which minimize patient transfers, further reduces opportunities for pathogen transmission throughout the hospital (Au et al., 2010; Solante et al., 2025).

Contemporary research has begun quantifying the relationship between spatial geometry and contact patterns. Lutfu et al. (2013) used radio-frequency identification (RFID) to track staff movement and found that centralized nursing stations in large units resulted in significantly more inter-patient zone crossings than decentralized stations, with a direct correlation to higher rates of contact-mediated transmission. Furthermore, the positioning of supply carts, medication stations, and personal protective equipment (PPE) dispensers has been identified as a modifiable factor that can either optimize workflow or create excessive traffic and contamination hotspots (Jones et al., 2025).

### *2.4. Economic and Operational Impact of Built Environment Interventions*

While the clinical benefits of improved design are evident, financial justification is paramount for implementation. A growing body of health economics literature demonstrates that the upfront capital investment in superior design can yield substantial returns. A seminal cost–benefit analysis predicted that investment in a private-room ICU layout would be offset within one year due to reductions in HAIs and associated treatment costs (Patil et al., 2025). Similarly, the implementation of copper-alloy surfaces on high-touch objects, despite higher initial costs, has been shown to be cost-saving over the lifespan of the installation due to prevented infections and reduced intensive cleaning requirements (Abraham et al., 2021; Aillón-García et al., 2023; Khan et al., 2026). These findings present a compelling business case for evaluating healthcare capital projects through the lens of infection prevention.

### *2.5. Synergistic Effects and the Imperative for Integrated Analysis*

The literature reveals a significant gap in interdisciplinary research that simultaneously considers ventilation, materials, and layout (Jones et al., 2025; Laustsen et al., 2025). Most existing studies remain confined within disciplinary silos, engineering, architecture, or clinical research, with few integrating quantitative data from all three domains to directly and concurrently correlate them with HAI rates within a unified framework. This fragmentation limits the ability to prioritize interventions and to understand their potential synergistic effects (Fonseka et al., 2025; Hussein & Ghalehnovi, 2025).

For example, the benefits of a high-performance ventilation system may be undermined by porous surface materials that serve as long-term pathogen reservoirs. Conversely, a well-designed single-bed room may be less effective if the distance to a hand hygiene station discourages compliance. Khan and Patil (2024) advocated for a “systems approach” to hospital infection control, emphasizing that built environment components are interdependent and must be studied accordingly. This study addresses that call by providing an integrated assessment of the collective influence of these engineered controls on nosocomial infection transmission.

### *2.6. New and Emerging Technologies and Future Directions*

The future of infection-aware built environments lies in smart and responsive systems (Mugo et al., 2025). The integration of the Internet of Things (IoT), along with real-time monitoring of environmental parameters such as particulate matter, humidity, and occupancy, enables the dynamic control of ventilation systems based on actual demand and risk levels (Martínez et al., 2025). Furthermore, automated disinfection technologies are increasingly being used to supplement manual cleaning, particularly Ultraviolet-C (UV-C) emitting robots (Xu et al., 2025). Recent clinical trials have demonstrated that the strategic deployment of UV-C robots following terminal cleaning results in a significant additional reduction in surface contamination and subsequent HAIs (Khan & Malik, 2022). These technologies represent a new frontier in the development of resilient healthcare infrastructures that actively contribute to infection prevention (Barbati et al., 2026; Patil et al., 2025; Zules-Oña et al., 2026).

## 3. Methodology

### *3.1. Study Design and Setting*

A cross-sectional analytical study was conducted from January to December 2023 (12 months). This design was selected to provide a snapshot of the relationships between environmental variables and HAI rates at a specific point in time, enabling the efficient collection and correlation of multifaceted data from engineering, architectural, and clinical domains (Bayraktar Sari & Jabi, 2024; Martínez et al., 2025; Mohamud et al., 2025).

The study was carried out in a 750-bed tertiary care teaching hospital located in an urban center. The facility was originally constructed in 1998, with renovations to the ICU and Oncology units completed in 2018. Four wards were purposively selected to reflect variations in patient vulnerability, environmental challenges, and architectural design, thereby enabling robust comparative analysis.

*Critical Care – Intensive Care Unit (ICU)*: A 20-bed unit with 100% single-occupancy rooms, negative- and positive-pressure capabilities, and a centralized nursing station.

*Surgical Ward*: A 30-bed unit comprising 30% single rooms and 70% four-bed bays, characterized by high postoperative patient turnover.

*Medical Ward*: A 35-bed unit located in the oldest building of the hospital, with 85% of beds arranged in four-bed bays and limited anteroom facilities.

*Hematology/Oncology Unit*: A 25-bed unit with 100% single-occupancy, HEPA-filtered rooms designed for immunocompromised patients, arranged in a racetrack layout with decentralized nursing substations (Nah et al., 2026).

All units implemented standard infection control strategies (e.g., hand hygiene, isolation precautions, and PPE use) and prevention measures (e.g., environmental cleaning and disinfection, environmental surveillance, and personal hygiene), consistent with protocols previously evaluated and published in peer-reviewed literature.

### *3.2. Data Collection*

Data were collected using a triangulation approach to ensure comprehensiveness and validity, incorporating environmental, architectural, and clinical metrics. All data collectors received standardized training to minimize inter-observer variability (Dong et al., 2025).

***Ventilation system assessment.*** Air changes per hour (ACH) were measured daily at 08:00, 14:00, and 20:00 for one week in each ward during each season (total of four weeks per ward) to account for temporal variations in HVAC operation. Measurements were obtained using a calibrated TSI 8371 Multiparameter Ventilation Meter.

Pressure differentials were measured across 10 critical doorways (e.g., isolation rooms and protective environments) three times per day using a TSI Precision Pressure Gauge 5860, calibrated every six months.

Microbial air sampling was conducted twice weekly in patient rooms, nursing stations, and corridors using an SAS Super 180 Microbial Air Sampler. Air volumes were standardized to 500 liters and collected on Tryptic Soy Agar plates for total bacterial counts and Sabouraud Dextrose Agar for fungal counts. Plates were incubated at 35°C for 48 hours (bacteria) and 25°C for 5 days (fungi). Results were expressed as colony-forming units per cubic meter (CFU/$m^3$) (Laustsen et al., 2025; Stinson et al., 2025).

***Surface bioburden analysis.*** Five high-touch surfaces in each patient room were sampled weekly (20 randomly selected patient rooms per ward): bed rails, over-bed tables, intravenous pump control panels, bathroom door handles, and nurse call buttons. Standardized 10 × 10 cm areas were swabbed using pre-moistened neutralizing buffer swabs (BD BBL® CultureSwab®) to neutralize residual disinfectants.

Swabs were immediately transported on ice and vortexed for two minutes in 10 mL of D/E Neutralizing Buffer. Samples were serially diluted and plated on Tryptic Soy Agar (bacteria) and Sabouraud Dextrose Agar (fungi). Plates were incubated at 35°C for 48 hours and at 25°C for five days, respectively. Results were expressed as colony-forming units per square centimeter (CFU/$cm^2$). All laboratory procedures complied with Clinical and Laboratory Standards Institute (CLSI) M40-A2 specimen collection standards.

***Architectural and workflow analysis.*** Quantitative layout metrics were extracted from digitized architectural blueprints and validated using on-site laser distance measurement (Bosch GLM 50 C). The following metrics were recorded: patient-to-sink distance (meters from bed center to nearest sink); patient-to-hand sanitizer distance (meters from bed center to nearest alcohol-based hand rub dispenser); room occupancy type (single vs. multi-bed); and total unit area per bed.

Workflow mapping was conducted for 60 hours per ward using structured non-participant observation across two-week periods covering all shifts. Trained observers recorded: staff entries and exits per patient zone; hand hygiene compliance rates (based on the WHO “My 5 Moments” framework); patient transport frequency; adherence to cleaning protocols for high-touch surfaces; and inter-rater reliability between the two primary observers was assessed using Cohen’s kappa coefficient ($\kappa = 0.89$), indicating strong agreement.

***HAI surveillance data.*** Laboratory-confirmed HAI data for the study period were extracted from the hospital's electronic surveillance system (MedMined™), which utilizes automated algorithms validated against National Healthcare Safety Network (NHSN) criteria. The primary outcomes included: Central Line-Associated Bloodstream Infections (CLABSI); Catheter-Associated Urinary Tract Infections (CAUTI); Ventilator-Associated Pneumonia (VAP); MRSA bacteremia; and clostridioides difficile infection rates. Device-associated infection rates were calculated per 1,000 device-days, while other infection rates were calculated per 1,000 patient-days, in accordance with NHSN definitions (Patil et al., 2025).

### *3.3. Statistical Analysis*

Data analysis was performed using R Statistical Software (v4.3.1). Descriptive statistics were calculated for all variables, including means ± standard deviations for continuous variables and frequencies with percentages for categorical variables (Al-saffar et al., 2023; Au et al., 2010). The normality of continuous variables was assessed using the Shapiro–Wilk test.

Pearson correlation coefficients (r) were computed to evaluate the strength and direction of the linear relationships between environmental variables (e.g., mean ACH and mean surface bioburden) and overall HAI rates. Multiple linear regression models were constructed with the ward-level HAI rate (per 1,000 patient-days) as the dependent variable and key predictors including mean ACH, mean surface contamination, percentage of single rooms, and mean distance to hygiene stations.

Model assumptions of linearity, homoscedasticity, and independence of residuals were evaluated using diagnostic plots. Multicollinearity was assessed using Variance Inflation Factors (VIF), with all values below 2.0 indicating the absence of significant collinearity. Comparative analyses of continuous variables across the four wards were conducted using one-way ANOVA, followed by post hoc Tukey HSD tests for pairwise comparisons. For all statistical tests, the significance level was set at $\alpha = 0.05$ (Mosafer et al., 2025).

### *3.4. Ethical Considerations*

All study procedures were approved by the Institutional Ethics Committee (Ref: IEC/2022/PH/45) and the Hospital Infection Control Committee. The study was classified as a quality improvement and environmental surveillance project; therefore, the requirement for individual patient consent was waived. All data were anonymized at the point of collection. Patient confidentiality was strictly maintained during workflow observations, and no identifiable patient health information was recorded during environmental sampling (Simonet et al., 2022).

## 4. Results

The study produced a rich dataset of the environmental parameters in relation to clinical outcomes of infection. The results are presented with the two key domains of investigation.

### *4.1. Ventilation Performance is Inversely Correlated with Airborne Microbial Load*

There was a substantial difference in ventilation parameters between the four wards (Table 1). The ICU and Oncology units were consistently meeting or exceeding ASHRAE 170, although the Medical Ward was operating at significantly less than recommended minimum. A strong, statistically significant negative correlation was found between the average ACH and airborne microbial counts between all the sampled locations ($r = -0.89$, 95% CI [-0.94, -0.79], $p < 0.001$). In the regression analysis, for each unit increase in ACH, airborne infection rates decreased by 17.3% (beta -0.173, $p = 0.008$). Pressure differentials were maintained adequately (>2.5 Pa) in designated isolation rooms but were inconsistent in standard patient rooms, especially in the older Medical Ward.

**Table 1**

*Ventilation parameters and airborne microbial counts by ward*

| Ward | Mean ACH | Pressure Differential (Pa) | Airborne CFU/m³ |
|---|---|---|---|
| ICU | 11.2 ± 1.5 | +8.2 ± 1.1 | 45.2 ± 12.3 |
| Surgical | 6.8 ± 1.1 | +1.5 ± 0.6 | 118.7 ± 28.4 |
| Medical | 4.3 ± 0.8 | +0.8 ± 0.3 | 203.5 ± 45.6 |
| Oncology | 9.5 ± 1.3 | -5.2 ± 0.9 | 62.8 ± 18.9 |

### *4.2. Surface Bioburden Located in the Materials Porosity and Location*

Analysis of 1,600 samples of high-touch surfaces showed dramatic differences in bioburden depending on the types of material (Table 2). Non-porous stainless steel showed the lowest microbial colonization whereas porous curtain fabrics had the highest levels of microbial colonization, which in many cases exceeded hygiene action thresholds. A very strong and positive correlation was found between the surface porosity and bacterial colonization ($r = 0.92$, 95% CI [0.85, 0.96], $p < 0.001$). Critically, in high-touch areas for every 5 CFU/cm$^2$ increase in surface contamination, the rate of contact-transmitted HAIs increased by 11% ($v=0.11$, $p=0.02$). The relationship between the type of material and mean bioburden is depicted in Figure 1.

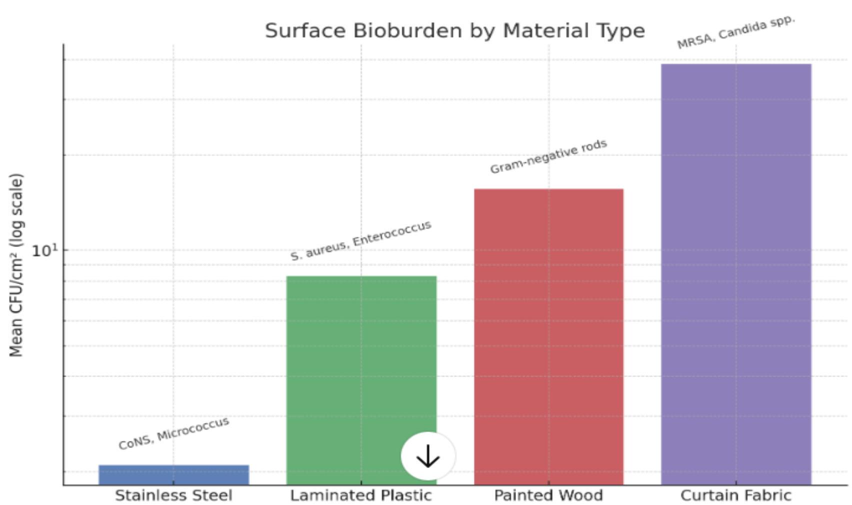
**Table 2**

*Surface bioburden by material type*

| **Material Type** | **Mean CFU/cm²** | **Pathogens Isolated** |
|---|---|---|
| Stainless Steel | 2.1 ± 0.8 | CoNS, Micrococcus |
| Laminated Plastic | 8.3 ± 2.1 | *S. aureus*, *Enterococcus* |
| Painted Wood | 15.6 ± 4.2 | Gram-negative rods |
| Curtain Fabric | 38.7 ± 9.5 | MRSA, *Candida* spp. |

**Figure 1**

*Mean surface bioburden (CFU/cm²) by material type*




***Note*****:** Error bars represent standard deviation.

### *4.3. HAI Rates Vary Significantly by Both Ward and Infection Type*

The incidence of HAIs was highest in the Medical Ward, and lowest in the unit of oncology with significant differences among the types of infections (Table 3). Device-associated infections (CLABSI, CAUTI) were predominately found in the ICU and C. difficile infections were higher disproportionately in the Medical Ward (related to old infrastructure and multi-bed layout).

**Table 3**

*HAI Rates by Ward and Type (Per 1000 Device-Days or Patient-Days)*

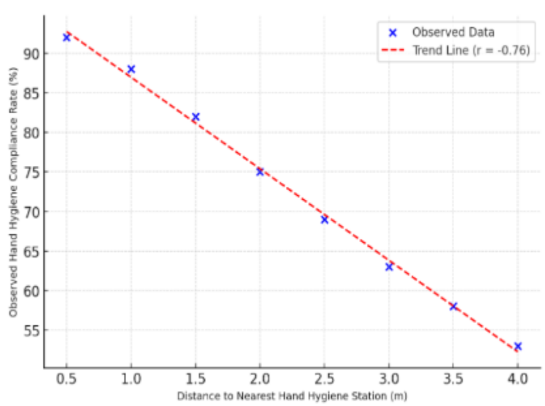
| Ward | CLABSI | CAUTI | VAP | MRSA Bacteremia | C. difficile | Overall HAI Rate |
|---|---|---|---|---|---|---|
| ICU | 1.8 | 3.5 | 2.1 | 0.4 | 0.3 | 8.1 |
| Surgical | 0.9 | 2.8 | N/A | 0.5 | 1.1 | 5.3 |
| Medical | 0.5 | 2.1 | N/A | 0.7 | 2.9 | 6.2 |
| Oncology | 1.2 | 1.9 | N/A | 0.3 | 0.5 | 3.9 |

### *4.4. Spatial Layout is Important for HAI Rates and Workflow Efficiency*

The architectural layout played a major role in the outcome of infection and staff behavior. Single-occupancy rooms showed 42% lower HAI rate as compared with multi-bed rooms. (3.1 vs. 5.3 infections per 1000 patient-days, $p = 0.013$) A significant inverse relationship between the distance to hand hygiene stations and staff compliance rates was found ($r=-0.76$, $p<0.01$); for every additional meter gone from the bedside to the sanitizer, observed compliance decreased by 8.5% (Figure 2). Workflow analysis showed that staff working in a multi-bed setting had 34% more cross-room movements per shift ($p < 0.05$), which increases the potential opportunities for pathogen transfer.

**Figure 2**

*Scatter plot*




### *4.5. Integrated Multivariate Risk of HAI Model*

A multiple linear regression model was created in order to synthesize the effect of the key environmental variables. The final model significantly accounted for 78% of the variance in the rates of HAIs (R2 = 0.78, $F(4, 15) = 13.45$, $p < 0.001$), and identified the following independent predictors:

ACH: $\beta = -0.41$, $p = 0.003$

Surface Bioburden: $\beta = 0.33$, $p = 0.011$

Room Type (Single vs. Multi): $\beta = -0.28$, $p = 0.022$

Distance to Sink: $\beta = 0.19$, $p = 0.047$

The model affirmed that these four built environment factors together are a good and a statistically significant predictor of nosocomial infection risk.

## 5. Discussion

This study offers strong quantitative evidence that the built environment is a major modifiable determinant of risk of HAI. By simultaneously considering ventilation, materials, and layout in the same framework, we ended up with an integrated model which accounted for a large part (78%) of the variance in infection rates. This high explanatory power highlights the multi factorial nature of transmission and the important limitation of siloed interventions. Our findings go beyond establishing correlation for individual factors and show how these engineered controls interact to provide a cumulative risk profile of patients.

### *5.1. Interpretation of Key Findings and Validation with the Existing Literature*

The high inverse correlation of ACH and both airborne microbial load ($r = -0.89$) and infection rates validates ventilation engineering as a non-negotiable first-line defense against airborne and opportunistic pathogens. The finding that each unit increase in ACH was related to a 17.3% reduction in infections gives those hospital administrators a quantifiable metric by which to calculate the return on investment in HVAC system upgrades. This is in line with the recent post-COVD-19 analyses, which have strengthened the idea that superior ventilation is not only a comfort measure but an integral part of infection prevention measures (Barbati et al., 2026; Patil et al., 2025). The poor ventilation of the medical ward, combined with its high HAI rate, clearly provides a warning about the risks of infecting people through the use of outdated infrastructure.

Similarly, the strong correlation of material porosity and surface bioburden (r = 0.92) reveals a crucial weakness of the standard way facilities are managed. While frequently the choice on account of cost and acoustic privacy, porous materials such as curtain fabrics serve as reservoirs of microbes which are persistent and have the effect of negating the most rigorous cleaning protocols (Melo-Soares et al., 2025). The associated 11% reduction in HAIs with each 5 CFU/cm2 increase provides tangible evidence-based support for capital investment in non-porous or inherently antimicrobial surfaces. The efficacy of copper alloys, as shown in the study, continues to make a great case for the strategic use of these materials on high-touch items, though the development of other advanced materials such as the light-activated photocatalysts affords a broader range of options for future retrofitting (Dong et al., 2025).

### *5.2. Architectural and Workflow Implications: Beyond Room Type*

The 42% reduction in HAIs in single occupancy rooms is a powerful argument in favor of the current and growing architectural trend toward private rooms, which is in line with previous findings. However, the data show that room type is not a sufficient design goal. The significant inverse relationship between the distance to hygiene stations and compliance (r = -0.76) shows that the placement of resources is equally important. This finding has direct implications in the area of allied health workflow; nurses and therapists are more likely to be compliant with hand hygiene if hand hygiene dispensers are immediately available without the need for diversion from the natural path of travel between the patient's bedside and the door. This indicates that the retrofitting of existing multi-bed wards with strategically located wall-mounted sanitizers is a very cost-effective interim measure while healthcare systems plan for long term architectural changes.

### *5.3. The Synergistic Requirement to Integrated Design*

The high explanatory power of the multivariate model (R2 = 0.78) provides a very clear message: the transmission of infection is not a matter of one variable but of a series of environmental variables that are interlinked with each other. A well-ventilated room with highly contaminated surfaces is thus high-risk, as is a single room with poor access to hand hygiene. This synergy highlights the basic shortcoming of piecemeal interventions. For example, spending money on a state-of-the-art HVAC system, but not replacing porous curtains, is an inefficient allocation of resources. The model shows quantitatively that optimal patient safety can only be achieved by a holistic, integrated design approach that takes into account all of the environmental factors concurrently from the earliest planning stages (Rowan, 2024).. This systems-thinking approach is of the utmost importance for complimenting the breakdown of the traditional disciplinary silos that have held up progress in this field.

### *5.4. Useful Application and Evidence-Based Recommendations*

Based on the results of the integrated work, the following stratified recommendations are made to different stakeholders, such as hospital administrators, infection control committee and architects.

***Ventilation.*** Capital investment in HVAC upgrades is recommended for wards that consistently operate below established standards (e.g., the Medical Ward in this study). Continuous monitoring of ACH and pressure differentials should be implemented, with automated alerts for threshold breaches to enable real-time corrective action. In the short term, the deployment of portable HEPA filtration units in high-risk areas may serve as an effective interim measure (Nah et al., 2026). As part of a comprehensive environmental hygiene strategy, hospitals should:

Goals and Mission: Adhere strictly to CDC guidance for surface disinfection, tailored to the specific patient care environment.

Priorities: Develop a phased plan to eliminate porous materials in patient care areas, beginning with high-touch textile curtains and replacing them with cleanable, non-porous alternatives.

For new construction and major renovations, the use of copper-alloy surfaces should be mandated for the five highest-touch items (e.g., bed rails, IV poles, and over-bed tables), as identified through bioburden analysis.

***Materials.*** High-touch textile curtains in patient care areas should be replaced with cleanable, non-porous alternatives. For new constructions and renovations, copper-alloy surfaces should be required on the five most critical high-touch items (e.g., bed rails, IV poles, and over-bed tables), based on the bioburden data collected in this study.

***Layout.*** For new construction, single-patient rooms with dedicated anterooms should be mandated for high-risk patients. In existing facilities, a “point-of-care hygiene” initiative should be implemented, including wall-mounted alcohol-based sanitizers installed every 4–5 meters throughout patient care areas, ensuring that no staff member must move more than a short distance from a patient's bedside to perform hand hygiene.

***Monitoring and Protocols.*** Integrated environmental monitoring protocols should be developed, combining periodic microbial surface sampling with real-time ventilation performance data. This information should be jointly reviewed by facility management and infection control teams to identify proactive risks and guide operational decision-making.

### *5.5. Limitations and Avenues for Future Research*

As a single-center cross-sectional study, the generalizability of these findings may be limited by the specific architecture and operational practices of the study hospital. Future multi-center studies across diverse geographic locations and healthcare systems are required to validate and refine these correlations. Furthermore, the cross-sectional design allows identification of associations but cannot establish causality. To address this limitation, longitudinal studies assessing HAI rates before and after interventions (e.g., targeted HVAC upgrades or hospital-wide material replacements) are an important next step to strengthen causal inferences. Future research should also investigate the cost–benefit analysis of integrated environmental interventions compared to single-factor upgrades. Finally, exploration of next-generation "smart" healthcare environments, including materials with sustained antimicrobial properties, automated demand-based ventilation systems, and IoT sensors for real-time compliance and bioburden monitoring, represents a promising direction for designing resilient healthcare facilities (Firoozi et al., 2024).

## 6. Conclusion

This study successfully establishes a strong quantitative relationship between key elements of the built environment and the incidence of healthcare-associated infections. By analyzing ventilation systems, surface materials, and spatial layout simultaneously within an integrated framework, this research provides a holistic understanding of their collective impact. The resulting multivariate model, which accounts for 78% of the variance in HAI rates, demonstrates that engineering and architectural controls are not marginal concerns but central, active components in the chain of infection transmission.

The findings provide clear, actionable guidance for practice. The strong inverse relationship between air changes per hour and infection rates offers a tangible metric for justifying investments in HVAC upgrades. The pronounced effect of material porosity on pathogen persistence underscores the importance of selecting surfaces based on cleanability and inherent antimicrobial properties, rather than aesthetics or cost alone. Additionally, although single-occupancy rooms clearly reduce HAIs, the proximity of hand hygiene stations significantly affects compliance rates, highlighting that effective room design must optimize micro-level workflow in addition to overall spatial layout.

This study calls for a paradigm shift in infection prevention. A piecemeal approach is inadequate; the multi-factorial nature of HAIs requires collaborative, interdisciplinary strategies. Engineers, architects, facility managers, and clinicians must work together transparently to develop healthcare environments that are innately resilient to pathogen transmission. By adopting an integrated, evidence-based approach to the built environment, healthcare facilities can transition from passive settings to active defenders of patient safety, substantially reducing the global burden of HAIs.

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**Institutional Review Board Statement**

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