ANNEX 78

EBC

Energy in Building and
Communities Programme

International Energy Agency

Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications (Annex 78)

Subtask D Long term field validation of gas phase air cleaning

Energy in Buildings and Communities
Technology Collaboration Programme

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Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications (Annex 78)

Energy in Buildings and Communities Technology Collaboration Programme

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 30 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of 'low tech', robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
- the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 78: Cost Effective Energy and CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)

Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
Annex 63: Implementation of Energy Strategies in Communities (*)
Annex 64: LowEx Communities - Optimised Performance of Energy Supply Systems with Exergy Principles (*)
Annex 65: Long-Term Performance of Super-Insulating Materials in Building Components and Systems (*)
Annex 66: Definition and Simulation of Occupant Behavior in Buildings (*)
Annex 67: Energy Flexible Buildings (*)
Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings (*)
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale (*)
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements (*)
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings (*)
Annex 73: Towards Net Zero Energy Resilient Public Communities (*)
Annex 74: Competition and Living Lab Platform (*)
Annex 75: Cost-effective Building Renovation at District Level Combining Energy Efficiency and Renewables (*)
Annex 76: ☼ Deep Renovation of Historic Buildings Towards Lowest Possible Energy Demand and CO_2 Emissions (*)
Annex 77: ☼ Integrated Solutions for Daylight and Electric Lighting (*)
Annex 78: Supplementing Ventilation with Gas-phase Air Cleaning, Implementation and Energy Implications
Annex 79: Occupant-Centric Building Design and Operation
Annex 80: Resilient Cooling
Annex 81: Data-Driven Smart Buildings
Annex 82: Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems
Annex 83: Positive Energy Districts
Annex 84: Demand Management of Buildings in Thermal Networks
Annex 85: Indirect Evaporative Cooling
Annex 86: Energy Efficient Indoor Air Quality Management in Residential Buildings
Annex 87: Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems
Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89: Ways to Implement Net-zero Whole Life Carbon Buildings
Annex 90: ☼ EBC Annex 90 / SHC Task 70 Low Carbon, High Comfort Integrated Lighting
Annex 91: Open BIM for Energy Efficient Buildings
Annex 92: Smart Materials for Energy-efficient Heating, Cooling and IAQ Control in Residential Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities (*)
Working Group - Building Energy Codes

Executive Summary

Study Overview and Objectives

This comprehensive field study investigated the real-world effectiveness of three commercial air purifiers in office environments at the Czech Technical University in Prague. Unlike controlled laboratory studies, this research deliberately examined purifier performance under actual operating conditions, including natural user behaviors and environmental variability. The nine-phase experiment (E1-E9) spanned two seasonal periods—spring 2023 and winter 2023/2024—to capture the full range of conditions affecting air purifier performance in practice.

Methodology and Scope

Four office rooms were monitored continuously: three equipped with different air purification technologies and one reference room without purification. The study measured key pollutants including CO_2, formaldehyde, total volatile organic compounds (TVOC), and particulate matter, alongside environmental parameters such as temperature and humidity. Nine experimental configurations tested various operational scenarios including purifier on/off states, placebo modes without filters, and different ventilation rates. User satisfaction was systematically assessed through 78 questionnaire responses covering thermal comfort, air quality perception, air movement, humidity, and noise levels.

The experimental design intentionally incorporated real-world variability rather than attempting to control all variables, recognizing that practical effectiveness under actual operating conditions provides more actionable insights than idealized laboratory performance metrics.

Key Performance Findings

Air Purifier Effectiveness Results:

Only one of the three tested purifiers demonstrated measurable pollutant reduction capabilities. The Daikin Ururu MCK75JVM-K in Room R3 showed consistent effectiveness in reducing formaldehyde concentrations across both seasonal periods, utilizing its multi-stage filtration system combining electrostatic filtration, titanium apatite photocatalytic technology, and ionization. This purifier achieved statistically significant reductions in formaldehyde levels during both spring and winter experimental phases.

In contrast, the Ionic-Care Triton X6 in Room R1 and the Dyson Purifier Cool Gen1 TP10 in Room R2 failed to demonstrate significant impact on monitored pollutant concentrations under real-world operating conditions. These results highlight the substantial gap between manufacturer specifications based on laboratory testing and actual field performance in occupied spaces.

Seasonal Performance Variations:

Spring experiments consistently showed more pronounced purifier effects compared to winter periods, though overall results remained inconsistent across different room configurations and pollutant types. This seasonal dependency indicates that environmental factors such as temperature, humidity, outdoor air quality, and occupancy patterns significantly influence purifier performance in ways not captured by standardized testing protocols.

Critical Role of User Behavior

The study revealed that occupant behavior represents the most significant factor affecting air purifier effectiveness in practice, often superseding the technical capabilities of the equipment itself. Users frequently opened windows and doors for temperature regulation, particularly during spring periods when indoor temperatures became uncomfortable, substantially reducing purifier effectiveness through pollutant infiltration and treatment dilution.

Behavioral Compliance Challenges:

User cooperation systematically decreased over the extended experimental period as occupants became increasingly dissatisfied with operational restrictions. This finding exposes a fundamental tension in air purifier implementation between optimal technical performance requirements and user acceptance of the behavioral modifications necessary to achieve that performance.

Specific behavioral impacts included perfume use that interfered with TVOC measurements, inconsistent adherence to environmental control protocols, and prioritization of thermal comfort over air quality optimization. The non-standard office usage patterns observed—intermittent rather than continuous eight-hour occupancy—further complicated effectiveness assessments but accurately reflect modern flexible workplace conditions.

Subjective Environmental Quality Assessment

Questionnaire responses revealed complex relationships between objective air quality measurements and occupant satisfaction that varied significantly by room, season, and experimental condition. Room R1 demonstrated the most positive subjective improvements, with enhanced thermal comfort and air movement perception during winter purifier operation, though these benefits were not consistent across seasons.

Thermal Comfort Dominance:

Thermal comfort emerged as the primary factor influencing overall occupant satisfaction, frequently overshadowing any air quality improvements provided by purifiers. High temperatures during spring experimental phases led to general dissatisfaction regardless of purifier operation status, indicating that successful air purifier implementation must address broader indoor environmental quality factors beyond pollutant removal.

Even when measurable pollutant reductions occurred, users did not necessarily perceive corresponding improvements in air quality, and in some cases reported decreased satisfaction due to operational restrictions or perceived changes in airflow patterns.

Methodological Insights and Real-World Applicability

This study's approach of examining purifier performance under uncontrolled operating conditions provides crucial insights into the effectiveness gap between laboratory specifications and practical applications. The methodology successfully captured the variability and behavioral factors that significantly influence real-world performance but are typically excluded from standardized testing environments.

Implementation Challenges Identified:

The research identified several critical factors limiting air purifier effectiveness in practice: frequent envelope breaches through door and window opening, user resistance to operational restrictions, interference from occupant activities, and the complex interaction between purification systems and existing building environmental controls.

These findings suggest that air purifiers achieve optimal performance only under specific conditions that may not align with natural occupant preferences and behaviors, particularly in buildings where users have direct control over the indoor environment.

Strategic Recommendations

For Building Design and Operation:

Air purifiers demonstrate greatest potential in controlled environments where occupant behavior can be managed through building design rather than user compliance requirements. Integration with building automation systems that coordinate purifier operation with HVAC systems, occupancy patterns, and environmental controls may improve effectiveness while maintaining user comfort.

For Technology Selection:
Purifier selection should prioritize technologies that have demonstrated field effectiveness under actual operating conditions rather than relying solely on laboratory specifications. Multi-stage filtration systems with diverse pollutant removal mechanisms showed superior performance compared to single-technology approaches.

For Future Research:
Subsequent investigations should focus on environments where occupants naturally maintain closed indoor spaces, utilize larger sample sizes with standardized protocols, and examine economic analyses incorporating both direct costs and indirect benefits including health and productivity impacts.

Conclusions and Practical Guidance

This research demonstrates that air purifier effectiveness in real-world applications depends critically on the intersection of technology capabilities, user behavior, building design, and operational management. While air purifiers can provide meaningful air quality improvements under appropriate conditions, their practical effectiveness is substantially limited by factors typically excluded from laboratory evaluations.

The study's findings support a strategic approach to air purifier implementation that considers these technologies as components of integrated indoor environmental quality management systems rather than standalone solutions. Success requires careful attention to user acceptance, behavioral compliance strategies, and coordination with existing building systems.

Recommendation for Practice:
Future air purifier implementations should prioritize environments with controlled access to outdoor air, incorporate comprehensive user education programs, and consider automated systems that minimize behavioral compliance requirements while maintaining effectiveness. The research indicates that air purifiers achieve optimal results when integrated into broader building environmental management strategies rather than deployed as isolated interventions.

Table of content

Abbreviations

Organizations and Standards

Abbreviation	Meaning
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CTU	Czech Technical University in Prague
EBC	Energy in Buildings and Communities
ECBCS	Energy Conservation in Buildings and Community Systems
ESSU	Executive Committee Support Services Unit
IEA	International Energy Agency
ISO	International Organization for Standardization
OECD	Organisation for Economic Co-operation and Development
TCP	Technology Collaboration Programme

Technical Terms and Equipment

Abbreviation	Meaning
BIM	Building Information Modelling
CADR	Clean Air Delivery Rate
HEPA	High Efficiency Particulate Air
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
LCA	Life Cycle Analysis
PAC	Portable Air Cleaner
PM	Particulate Matter
R&D	Research and Development
VOC	Volatile Organic Compounds
TVOC	Total Volatile Organic Compounds

Measurement Units

Abbreviation	Meaning
°C	Degrees Celsius
µg/m³	Micrograms per cubic meter
m³/h	Cubic meters per hour
ppm	Parts per million
ACH	Air Changes per Hour
CFM	Cubic Feet per Minutes
dB	Decibels
W	Watts

kg	Kilograms
cm	Centimeters
l/s	Liters per second
µm	Micrometers (microns)

Chemical Compounds

Abbreviation	Meaning
CO_2	Carbon Dioxide
HCHO	Formaldehyde
PM_1	Particulate Matter with diameter ≤ 1 micrometer
$PM_{2.5}$	Particulate Matter with diameter ≤ 2.5 micrometers
PM_{10}	Particulate Matter with diameter ≤ 10 micrometers

Room Designations (Experimental Setup)

Designation	Description
R1	Room 1 with Air Purifier 1 (Ionic-Care Triton X6)
R2	Room 2 with Air Purifier 2 (Dyson Purifier Cool Gen1 TP10)
R3	Room 3 with Air Purifier 3 (Daikin Ururu MCK75JVM-K)
R4	Reference room without air purifier

Experiment Designations

Experiment	Period	Conditions Description
E1	Spring	Air purifier ON, closed windows/doors, lower ventilation rate
E2	Spring	Air purifier ON, user-controlled windows/doors, lower ventilation rate
E3	Spring	Placebo mode (purifier without filters), closed windows/doors, lower ventilation rate
E4	Spring	Air purifier OFF, closed windows/doors, higher ventilation rate
E5	-	Excluded from final evaluation due to non-standard operation
E6	Winter	Air purifier OFF, closed windows/doors, higher ventilation rate
E7	Winter	Air purifier ON, closed windows/doors, lower ventilation rate
E8	Winter	Placebo mode (purifier without filters), closed windows/doors, lower ventilation rate
E9	Winter	Air purifier ON with new filters, closed windows/doors, lower ventilation rate

Filter and Technology Types

Abbreviation	Meaning
MERV	Minimum Efficiency Reporting Value
ePM	Efficiency Particulate Matter (ISO 16890 classification)
H13	HEPA filter class (99.95% efficiency at 0.3 µm)
UV	Ultraviolet

Statistical and Assessment Terms

Abbreviation	Meaning
N/A	Not Available / Not Applicable
CFD	Computational Fluid Dynamics
REPL	Read-Eval-Print Loop

Building and System Components

Abbreviation	Meaning
AHU	Air Handling Unit
LCD	Liquid Crystal Display
WASP-XM	Wide Area Sampling Platform - Extended Monitoring

Questionnaire Assessment Scale

Numerical Value	Meaning
-3 to +3	Seven-point assessment scale (from very negative to very positive)
0	Neutral condition

Definitions

Energy source: source from which useful energy can be extracted or recovered either directly or by means of a conversion or transformation process.

Energy carrier: substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes.

Embodied energy: total energy consumed by all of the processes associated with the production of a building, from the mining and processing of natural resources to manufacturing, transport and product delivery.

Portable Air Cleaner/ Purifier (PAC): standalone air treatment device designed to remove airborne contaminants from indoor air through various filtration and purification technologies, typically serving a single room or defined space.

Clean Air Delivery Rate (CADR): standardized measure of the effectiveness of an air purifier in removing particles from the air, expressed as the volume of clean air produced per unit time, typically measured in cubic meters per hour (m^3/h) or cubic feet per minute (CFM).

Indoor Air Quality (IAQ): the chemical, physical, and biological characteristics of air within buildings and structures, particularly as they relate to the health and comfort of building occupants.

Indoor Environmental Quality (IEQ): comprehensive assessment of indoor conditions that affect occupant comfort, health, and productivity, including air quality, thermal comfort, lighting, and acoustic conditions.

Total Volatile Organic Compounds (TVOC): collective measure of all volatile organic compounds present in indoor air, typically expressed as micrograms per cubic meter ($\mu g/m^3$), representing the total concentration of carbon-containing chemicals that readily evaporate at room temperature.

Formaldehyde (HCHO): colorless, strong-smelling chemical compound commonly found in indoor environments as an air pollutant released from building materials, furniture, and various consumer products, measured in micrograms per cubic meter ($\mu g/m^3$).

Particulate Matter (PM): mixture of solid particles and liquid droplets suspended in air, classified by size including PM_{10} (particles with diameter ≤10 μm), $PM_{2.5}$ (≤2.5 μm), and PM_1 (≤1 μm).

HEPA Filter: High Efficiency Particulate Air filter that removes at least 99.97% of particles that have a size of 0.3 μm or larger, representing the most penetrating particle size for this filter type.

Electrostatic Filter: air cleaning technology that uses electrically charged surfaces or media to attract and capture airborne particles through electrostatic forces.

Photocatalytic Filter: air purification technology that uses photocatalysts (typically titanium dioxide) activated by light to decompose organic pollutants and microorganisms through oxidation reactions.

Activated Carbon Filter: filtration medium consisting of highly porous carbon material that removes gaseous pollutants, odors, and volatile organic compounds through adsorption processes.

Working Hours: standardized period for data collection and analysis, typically defined as 8:00 AM to 7:00 PM, Monday through Friday, representing normal office occupancy periods.

Placebo Mode: experimental condition where air purification devices operate without active filtration elements (filters removed or disabled) to isolate the effects of air circulation from actual purification processes.

Ventilation Rate: volume of outdoor air supplied to or removed from a space per unit time, typically expressed in cubic meters per hour (m^3/h) or air changes per hour (ACH).

Air Change Rate: number of times the entire volume of air in a space is replaced per hour through ventilation and infiltration processes.

Field Study: research conducted in actual operating environments rather than controlled laboratory conditions, designed to capture real-world performance and variability.

Seasonal Variation: systematic changes in measured parameters or system performance associated with different seasons, reflecting variations in temperature, humidity, outdoor air quality, and occupancy patterns.

User Compliance: degree to which study participants adhere to prescribed protocols or behavioral requirements during experimental periods.

Environmental Control: maintenance of specified indoor conditions through regulation of factors such as temperature, humidity, ventilation, and access to outdoor air.

Mechanical Ventilation: engineered system for air exchange that uses fans, ducts, and other mechanical components to control the movement of air into and out of a building or space.

Natural Ventilation: air exchange process driven by natural forces such as wind pressure and buoyancy effects, typically through operable windows, doors, and other building openings.

Building Envelope: physical separator between the conditioned and unconditioned environment of a building, including walls, floors, roofs, windows, and doors.

HVAC System: Heating, Ventilation, and Air Conditioning system that provides thermal comfort and acceptable indoor air quality through integrated climate control technologies.

Pollutant Removal Efficiency: measure of an air purification system's ability to reduce specific contaminant concentrations, typically expressed as a percentage reduction or as a time-based decay rate.

Average Hourly Decrease: calculated rate of pollutant concentration reduction per hour, determined by analyzing successive hourly measurements over a defined experimental period.

Concentration Gradient: spatial or temporal variation in pollutant levels within a space, often used to assess mixing effectiveness and purification system performance.

Subjective Assessment: evaluation based on occupant perceptions and reported experiences rather than objective measurements, typically collected through questionnaires or interviews.

Thermal Comfort: condition of mind expressing satisfaction with the thermal environment, influenced by factors including air temperature, humidity, air movement, and radiant temperature.

Acceptability Rating: subjective evaluation of whether specific environmental conditions are considered tolerable or satisfactory by occupants.

Satisfaction Scale: standardized rating system used to quantify occupant responses to environmental conditions, typically ranging from highly dissatisfied to highly satisfied.

1. Introduction

Indoor air quality has emerged as a critical determinant of occupant health, comfort, and productivity in modern built environments. With people spending approximately 90% of their time indoors, the quality of indoor air directly impacts public health outcomes and economic productivity on a global scale. Recent research has established clear links between poor indoor air quality and respiratory diseases, cardiovascular conditions, cognitive performance deficits, and reduced workplace productivity, making effective air quality management an essential component of sustainable building operation.

The challenge of maintaining acceptable indoor air quality has intensified with increasingly airtight building construction, the proliferation of synthetic materials that emit volatile organic compounds, and growing awareness of outdoor air pollution infiltration. Traditional approaches relying solely on ventilation systems face limitations in energy-conscious building design, where excessive outdoor air introduction conflicts with energy efficiency objectives. This tension has driven increased interest in supplementary air cleaning technologies that can improve indoor air quality while minimizing energy penalties associated with increased ventilation.

The integration of gas-phase air cleaning technologies with conventional ventilation systems represents a paradigm shift in building air quality management strategies. Rather than relying exclusively on dilution ventilation with outdoor air, supplemental air cleaning offers the potential to maintain acceptable indoor air quality while reducing energy consumption associated with conditioning large volumes of outdoor air. This approach is particularly relevant for addressing gaseous pollutants such as volatile organic compounds (VOCs) and formaldehyde, which are not effectively controlled by particulate filtration alone and require substantial ventilation rates for adequate dilution.

Portable air purifiers (PACs) equipped with gas-phase removal capabilities represent one implementation pathway for this supplementation strategy, offering localized air quality improvement without major infrastructure modifications. These devices employ various purification technologies including activated carbon adsorption, photocatalytic oxidation, ionization processes, and hybrid systems that combine multiple removal mechanisms. The appeal of portable gas-phase air cleaners lies in their flexibility for addressing specific pollutant sources, potential energy savings compared to increased ventilation, and feasibility for deployment in existing buildings without extensive retrofitting.

However, the effectiveness of gas-phase air cleaning as a ventilation supplement in real-world applications remains poorly understood despite extensive laboratory testing and theoretical models. The energy implications of substituting mechanical air cleaning for ventilation air depend critically on actual removal efficiencies, power consumption patterns, and the complex interactions between air cleaning devices and existing building environmental systems. Clean Air Delivery Rate (CADR) measurements and standardized removal efficiency tests, while essential for comparative assessment, are conducted under controlled conditions that may not accurately predict performance or energy trade-offs in actual occupied spaces.

Emerging field studies suggest a substantial gap between laboratory-measured air cleaner performance and effectiveness of gas-phase removal under real-world operating conditions. This performance gap has critical implications for the viability of supplementing ventilation with air cleaning technologies. The gap appears to result from multiple factors including variable pollutant sources and concentrations, complex airflow patterns in occupied spaces, user operational behaviors, and interactions with existing building environmental systems that affect both removal efficiency and energy consumption.

Users frequently operate gas-phase air cleaners at reduced speeds to minimize noise and energy consumption, limit operating hours, and modify environmental conditions in ways that impact removal effectiveness. The energy implications of these behavioral patterns may negate the anticipated energy benefits of reducing ventilation rates, particularly if air cleaners operate inefficiently or require higher power consumption to compensate for suboptimal operating conditions. Understanding these real-world performance characteristics is essential for accurate assessment of the energy trade-offs associated with ventilation supplementation strategies.

The effectiveness of supplementing ventilation with gas-phase air cleaning is significantly influenced by environmental factors that vary seasonally and geographically, with direct implications for both air quality outcomes and energy performance. Outdoor air quality, temperature, humidity, and occupant behavior patterns change substantially across seasons, potentially affecting both pollutant generation rates and removal efficiency while influencing the energy balance between air cleaning and ventilation strategies.

Winter periods with closed buildings and reduced natural ventilation may favor air cleaning supplementation due to limited outdoor air infiltration, but may also create conditions where gaseous pollutant concentrations accumulate despite active removal. Conversely, spring and summer conditions when natural ventilation may be preferred by occupants for thermal comfort can reduce the effectiveness of gas-phase air cleaning while potentially reducing the energy benefits of ventilation supplementation.

The interaction between portable gas-phase air cleaners and existing building environmental systems adds critical complexity to energy performance assessment. Mechanical ventilation systems, natural airflow patterns, and occupant-controlled environmental modifications such as window and door operation create dynamic conditions that influence contaminant mixing, removal efficiency, and the relative energy performance of air cleaning versus ventilation strategies in ways that cannot be predicted from laboratory testing alone.

Despite growing interest in supplementing ventilation with gas-phase air cleaning technologies, systematic field evaluations under realistic operating conditions remain limited. Most existing research focuses on controlled laboratory studies or short-term field deployments that may not capture the full range of factors influencing long-term effectiveness and energy implications. The relationship between objective air quality improvements, occupant satisfaction, and actual energy performance of gas-phase air cleaning supplementation is particularly poorly understood, yet critical for successful implementation of integrated ventilation and air cleaning strategies.

The energy implications of integrating portable gas-phase air cleaners with building environmental systems represent a significant knowledge gap with direct practical relevance. While air cleaning technologies may enable reduced ventilation rates and associated energy consumption, their own power requirements, impacts on thermal comfort, and effectiveness under varying operational conditions must be understood within the broader context of building energy performance. The net energy impact of ventilation supplementation depends on complex interactions between removal efficiency, operating patterns, and building system responses that cannot be predicted from individual component performance data.

This study addresses these knowledge gaps through a comprehensive field evaluation of gas-phase air cleaning performance as a ventilation supplement in actual office environments over extended operational periods. The research examines three different commercial gas-phase air cleaning technologies under realistic operating conditions, incorporating natural user behaviors, seasonal variations, and integration with existing building ventilation systems. The methodology deliberately prioritizes ecological validity over experimental control, recognizing that real-world effectiveness and energy performance depend critically on factors that are typically excluded from laboratory assessments.

The investigation combines continuous monitoring of key gaseous pollutants including formaldehyde and total volatile organic compounds, along with carbon dioxide and particulate matter, with systematic assessment of occupant perceptions of indoor environmental quality and energy consumption patterns. This comprehensive approach provides insights into the technical effectiveness of gas-phase air cleaning technologies, their energy implications, and their impact on user satisfaction and acceptance under realistic deployment conditions as ventilation supplements.

By examining gas-phase air cleaner performance across different seasonal conditions, with varying user behaviors and environmental controls, this research provides essential insights for building operators, facility managers, and policymakers seeking to implement effective and sustainable strategies for supplementing ventilation with air cleaning technologies. The findings contribute to the evidence base needed to evaluate the practical viability and energy implications of gas-phase air cleaning as a component of integrated building air quality and energy management strategies.

2. Literature Review

The systematic evaluation of portable air cleaner (PAC) effectiveness in real-world conditions has become the subject of growing scientific interest. A meta-analysis of 148 field studies conducted by Fazli and Stephens [15] represents the most comprehensive review of available knowledge. The authors found an average PM2.5 concentration reduction of 49 % with a standard deviation of 20 %. Results showed approximately normal distribution ranging from no significant reduction to maximum reductions above 90%.

Field studies in different types of environments confirm considerable performance variability. Curtius et al. [27] demonstrated the effectiveness of mobile air purifiers in reducing SARS-CoV-2 transmission risk under controlled classroom conditions, emphasizing the importance of proper device positioning. Similarly, Mousavi et al. [17] found in a study of nine university classrooms that combining PAC with ventilation systems can achieve high air exchange rates (2.63-8.63 h^{-1}) with significant particulate pollution reductions.

A key finding from systematic reviews is the identification of factors that significantly reduce PAC effectiveness in real-world operation compared to laboratory conditions. Fazli and Stephens [15] identified as the main problem the fact that users operate air cleaners for shorter periods and at lower fan speeds due to concerns about noise, drafts, and electricity costs, which significantly reduces air cleaning effectiveness.

Tham et al. [21] achieved 80-95% PM reduction using window-mounted PAC units during haze episodes in Singapore, but this required keeping windows and doors closed to create a positive pressure environment. These results indicate that PAC effectiveness is strongly dependent on controlling outdoor air access and user behavior.

Current methods for evaluating PAC performance are based primarily on standardized testing procedures. ASHRAE Standard 52.2-2017 [25] defines methodology for testing air cleaning efficiency by particle size using MERV ratings (1-16). The newer international standard ISO 16890-1:2016 [24] introduces classification based on particulate matter capture efficiency (ePM1, ePM2.5, ePM10), which better corresponds to current understanding of air pollution health impacts.

A significant challenge in evaluating PAC is the difference between laboratory and field performance. Stephens et al. [3] highlight the energy implications of using PAC in buildings, emphasizing the need for optimization between air cleaning efficiency and energy consumption.

The ASHRAE Position Document on Indoor Air Quality [30]) establishes air cleaning as one of three fundamental approaches to improving IAQ, alongside source control and ventilation. ASHRAE explicitly states that effective air cleaning technologies should be used to "remove contaminants from outdoor ventilation air and recirculated indoor air." This represents official recognition of PAC as a legitimate IAQ improvement strategy.

The position emphasizes that achieving good IAQ can be accomplished through strategies that both secure high indoor air quality and reduce energy use, including increased envelope airtightness, heat recovery ventilation, demand-controlled ventilation, and improved system maintenance. This challenges the common assumption that good IAQ necessarily requires increased energy consumption.

Health benefits of PAC use have been documented in several controlled studies. Allen et al. [20] demonstrated improved endothelial function in healthy adults in a wood smoke-impacted community. Van der Heide et al. [22] found significant reduction in nocturnal symptoms including stuffy nose in asthmatic children sensitized to pet allergens in a double-blind, placebo-controlled study.

Recent evidence has also suggested that pollutants in indoor air may reduce cognitive function, with studies showing associations between CO_2, ventilation, and volatile organic compound exposures and cognitive performance in office workers. Barn et al. [16] conducted a randomized controlled trial examining the effect of HEPA filters during pregnancy on fetal growth, extending the evidence base for long-term health impacts of improved household air quality.

The economic case for PAC implementation has been strengthened by comprehensive cost-benefit analyses. Studies consistently show that the health and economic benefits of improved IAQ are far greater than the costs of implementing these improvements. Fisk and Chan (2017) estimated benefit-to-cost ratios ranging from three to 133 for the use of filters and/or portable air cleaners in both residences and commercial buildings.

The economic benefits accrue from multiple sources: higher worker productivity, improved learning outcomes, lower absentee rates, and reduced healthcare costs. In workplaces, measures that result in even small improvements in performance or absence are often cost-effective because employee costs far exceed the costs of maintaining good IAQ. Bekö et al. [31] estimated that health and productivity benefits of higher-performance filters would exceed their costs by well over a factor of 10 in an example office building.

Current research emphasizes the importance of integrating PAC with existing ventilation systems. ANSI/ASHRAE Standard 62.1-2022 [23] establishes basic requirements for commercial building ventilation while allowing the use of air cleaning as a supplementary method to traditional outdoor air ventilation within the Indoor Air Quality Procedure (IAQP).

ASHRAE's official position recognizes that many strategies exist that can help achieve good IAQ with lower energy impacts through an integrated design approach that considers both IAQ and energy, in addition to other key aspects of building performance. This includes the development of more dynamic ventilation strategies that allow time shifting and other variable ventilation approaches.

Shao et al. [18] used CFD simulations of an office space (45 m^2) to analyze interactions between cleaned air flows from PAC and background airflows generated by ventilation systems. They found that PAC position and capacity along with HVAC ventilation rate critically affect overall effectiveness.

Curtius et al. [27] tested mobile air purifiers in a school classroom during the COVID-19 pandemic and found significant reduction in airborne transmission risk. Simona et al. [5] conducted a randomized crossover trial with portable HEPA filters in classrooms, emphasizing the importance of controlled experimental conditions. The ASHRAE position document notes that ventilation and IAQ improvements in educational facilities can lead to improved learning outcomes and reduced absenteeism.

Lu et al. [6] evaluated PAC effectiveness in homes with wood heating, representing a specific type of source pollution. Barn et al. [19] recommended PAC as a priority measure for reducing PM2.5 exposure from biomass during wildfires, emphasizing their rapid deployment capability and effectiveness.

The ASHRAE document emphasizes that personal and indoor exposures to many airborne contaminants are commonly higher than outdoor exposures, and the majority of human exposure to outdoor contaminants typically occurs indoors due to the large amount of time people spend indoors.

Chen et al. [4] analyzed energy-efficient PAC operation based on real-time monitoring and optimization, representing a new research direction focused on reducing operating costs while maintaining air cleaning effectiveness.

The ASHRAE position challenges the traditional view that good IAQ requires increased energy consumption, stating that "many strategies exist that can both secure high IAQ and reduce energy use." This includes advanced system maintenance, smart ventilation strategies, and integrated design approaches that optimize both energy performance and indoor air quality.

Kelly and Fussell [26] in their comprehensive review of IAQ technologies identified the need for further research to establish links between air purification and health improvements. They emphasized the need for studies covering various environments including homes, schools, offices, and transportation.

The ASHRAE position document identifies several priority research areas including: the relationship of ventilation rates and contaminant concentrations to occupant health and performance; approaches to improving IAQ beyond dilution ventilation; development of monitoring and HVAC equipment to control IAQ by measurement of contaminants; and research on new contaminants of concern.

Current literature indicates several key areas requiring further research:

- Long-term effectiveness: Most studies focus on short-term effects, while data on long-term performance and sustainability of effects are limited.
- User behavior: Systematic understanding of factors affecting compliance with recommended operating conditions is insufficient.
- Building interactions: Complex interactions between PAC, HVAC systems, and building characteristics require additional CFD modeling and field validation.
- Evaluation standardization: Need for harmonization between different testing standards (ASHRAE 52.2, ISO 16890) and their relationship to real-world performance.
- Economic valuation tools: Development of tools to allow economic valuation of IAQ benefits for individual buildings and groups of buildings.

The current state of knowledge provides a solid foundation for understanding PAC technology potential while identifying significant gaps that limit their optimal implementation in real-world conditions. The official ASHRAE position provides strong institutional support for PAC technologies as part of a comprehensive IAQ strategy, recognizing that "the provision of acceptable IAQ is an essential building service and central to ASHRAE's purpose."

The convergence of evidence from field studies, economic analyses, and health research, combined with official recognition from leading professional organizations, establishes PAC as a legitimate and potentially cost-effective component of building IAQ management strategies. However, successful implementation requires careful attention to user behavior, system integration, and long-term performance optimization.

3. Methodology

The methodology employed in this study represents a deliberate departure from conventional laboratory-based air purifier testing protocols. Rather than attempting to create idealized conditions that maximize purifier performance, this research was designed to capture the complex reality of air purification technology deployment in actual occupied office environments. This field-based approach recognizes that the gap between laboratory performance specifications and real-world effectiveness often determines the practical value of air quality improvement technologies.

The experimental design prioritizes ecological validity over experimental control, acknowledging that factors such as user behavior, environmental variability, and operational constraints fundamentally influence air purifier performance in ways that cannot be replicated in controlled laboratory settings. This methodology responds to the growing recognition in indoor air quality research that standardized testing conditions, while useful for comparative technology assessment, may not accurately predict performance outcomes in the diverse and dynamic conditions of actual building operation.

Traditional air purifier evaluation methods typically employ standardized test chambers with controlled pollutant injection, fixed air exchange rates, and predetermined operational cycles. While these approaches provide reproducible comparative data, they systematically exclude the behavioral, environmental, and operational factors that significantly influence real-world performance. The present study was designed to address this limitation by incorporating the inherent variability of occupied office environments as a fundamental component of the assessment methodology.

The decision to conduct experiments in actively used office spaces, with natural occupancy patterns and user-controlled environmental conditions, reflects the understanding that air purifier effectiveness is not solely determined by the technical specifications of the purification technology. Instead, performance outcomes result from complex interactions between purification capabilities, building characteristics, occupant behaviors, and environmental conditions that vary temporally and spatially in ways that cannot be adequately simulated in laboratory environments.

The selection of office environments at the Czech Technical University in Prague was based on several key criteria that support the study's objective of assessing real-world air purifier performance. These spaces represent typical academic office environments with characteristics common to many commercial building applications, including intermittent occupancy patterns, user control over environmental conditions, and integration with mechanical ventilation systems.

The chosen offices feature controlled mechanical ventilation systems that allow for systematic manipulation of air exchange rates while maintaining other aspects of natural building operation. This configuration enables the isolation of specific variables while preserving the complex environmental interactions that characterize actual building performance. The offices' typical occupancy by individual users, with occasional visitors for short periods, reflects common workplace utilization patterns that differ substantially from the continuous occupancy assumptions underlying many air purifier specifications.

The non-standard usage patterns observed in these academic offices—where primary users occupy spaces intermittently throughout the day rather than maintaining continuous presence—provide insights into air purifier performance under variable occupancy conditions that are increasingly common in flexible workplace environments. This occupancy variability introduces realistic challenges for air purification systems that must respond to changing pollutant generation rates and user behavioral patterns.

The methodology incorporates both quantitative pollutant concentration measurements and qualitative user experience assessments to provide a comprehensive evaluation of air purifier performance that extends beyond traditional technical metrics. This dual approach recognizes that indoor environmental quality encompasses both measurable physical parameters and subjective human responses that together determine the practical value of air quality interventions.

The systematic collection of user perceptions through structured questionnaires provides insights into the relationship between objective air quality improvements and occupant satisfaction, addressing a critical gap in traditional air purifier assessment. This approach acknowledges that even technically effective air quality interventions may fail to achieve their intended benefits if they negatively impact other aspects of indoor environmental quality or require behavioral modifications that users find unacceptable.

The two-phase experimental design, spanning spring and winter periods with a strategic four-month interval, was implemented to capture the significant seasonal variations that affect both air purifier performance and user behavior. Seasonal differences in outdoor air quality, temperature, humidity, and occupant environmental management behaviors represent major factors influencing indoor air quality outcomes that are typically excluded from standardized testing protocols.

The temporal structure of the experiment acknowledges that both purifier performance and user acceptance may evolve over extended operational periods in ways that cannot be captured through short-term assessments. The systematic evaluation of user compliance and satisfaction over multiple experimental phases provides insights into the sustainability of air purifier implementation strategies and the factors that influence long-term effectiveness.

The methodological approach deliberately incorporates elements that traditional experimental design might classify as limitations, recognizing that these factors represent fundamental characteristics of real-world air purifier deployment. User non-compliance with environmental control protocols, variable occupancy patterns, and behavioral adaptations to purifier operation are treated as essential components of the assessment rather than confounding variables to be eliminated.

This approach reflects the understanding that successful air purifier implementation must account for these factors rather than assuming they can be controlled through design specifications or user education. The methodology therefore provides insights into both the potential and limitations of air purification technologies under the conditions they will actually encounter in practice.

3.1 Testbed CTU

An office building at the Czech Technical University (CTU) in Prague was chosen for the study. The focus was on Indoor Environmental Quality (IEQ) in real-world office settings, specifically examining the effectiveness of various commercial air-cleaners utilizing phase change technologyThe testbed consisted of four offices located on the second floor of the building [Fig. 1, 2]. Each office was equipped with controlled mechanical ventilation system to ensure precise conditions for the study [Fig. 2,3]. Typically, these offices were occupied by one person, but occasionally, a teacher and a few students would join for short periods. These offices were not typical workspaces, as the primary users were teachers who did not occupy them for a full eight-hour workday. Instead, they used the offices intermittently throughout the day, from 8 AM to 8 PM, whenever they were not engaged in lectures.

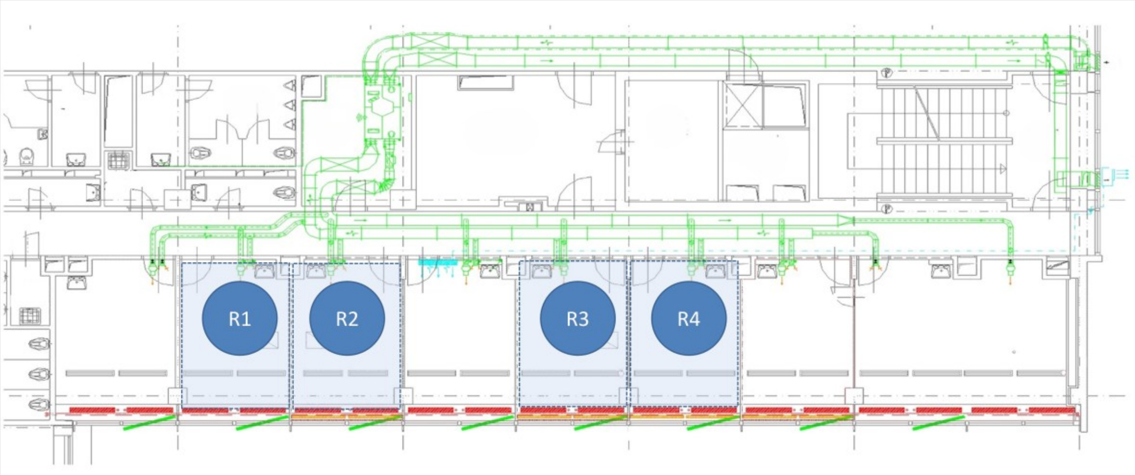


Fig. 1: Floor plan of the monitored object with marked incriminated rooms

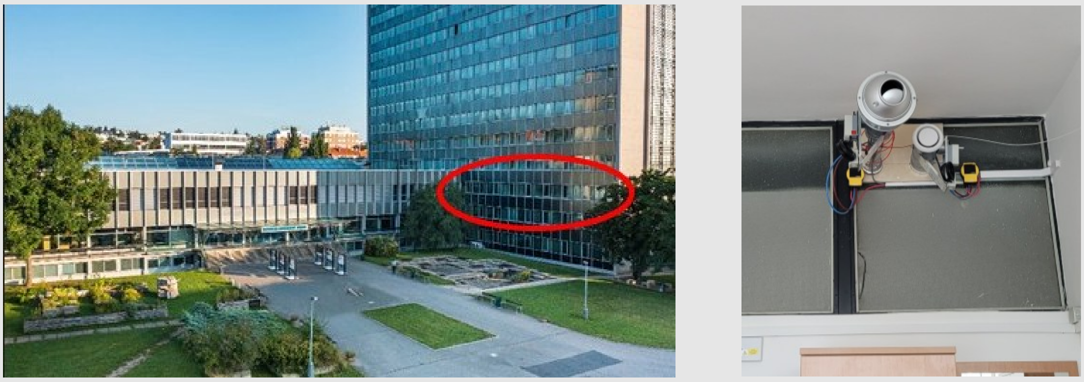


Fig. 2: The location of the examined rooms within the building and the distribution elements of the ventilation system in the room

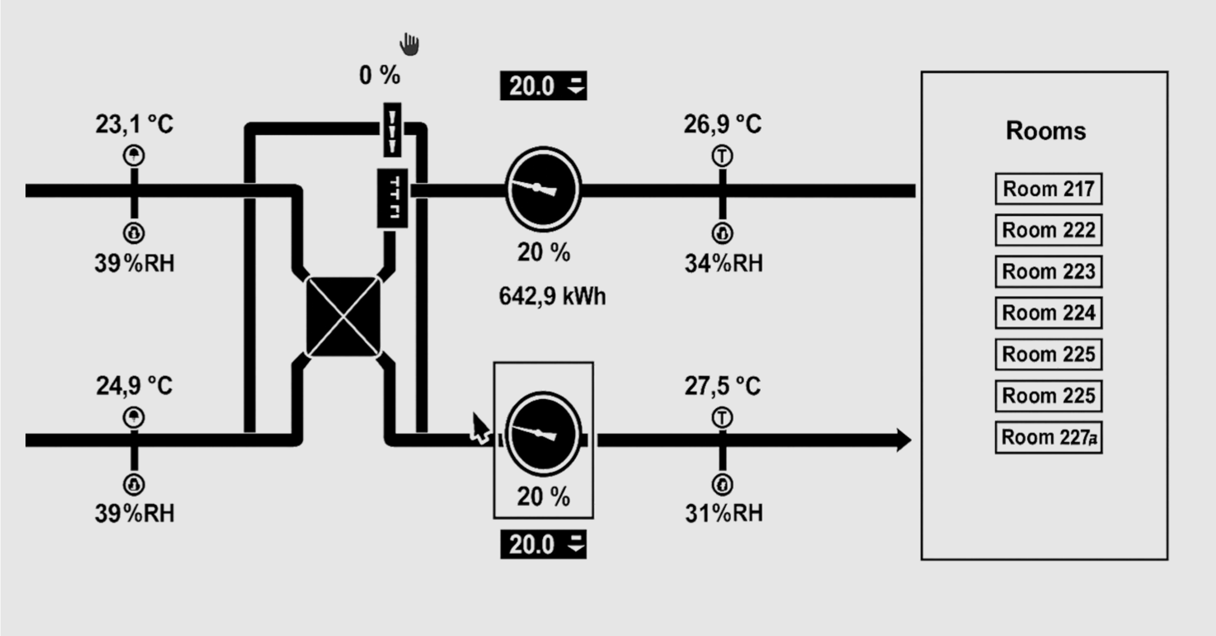
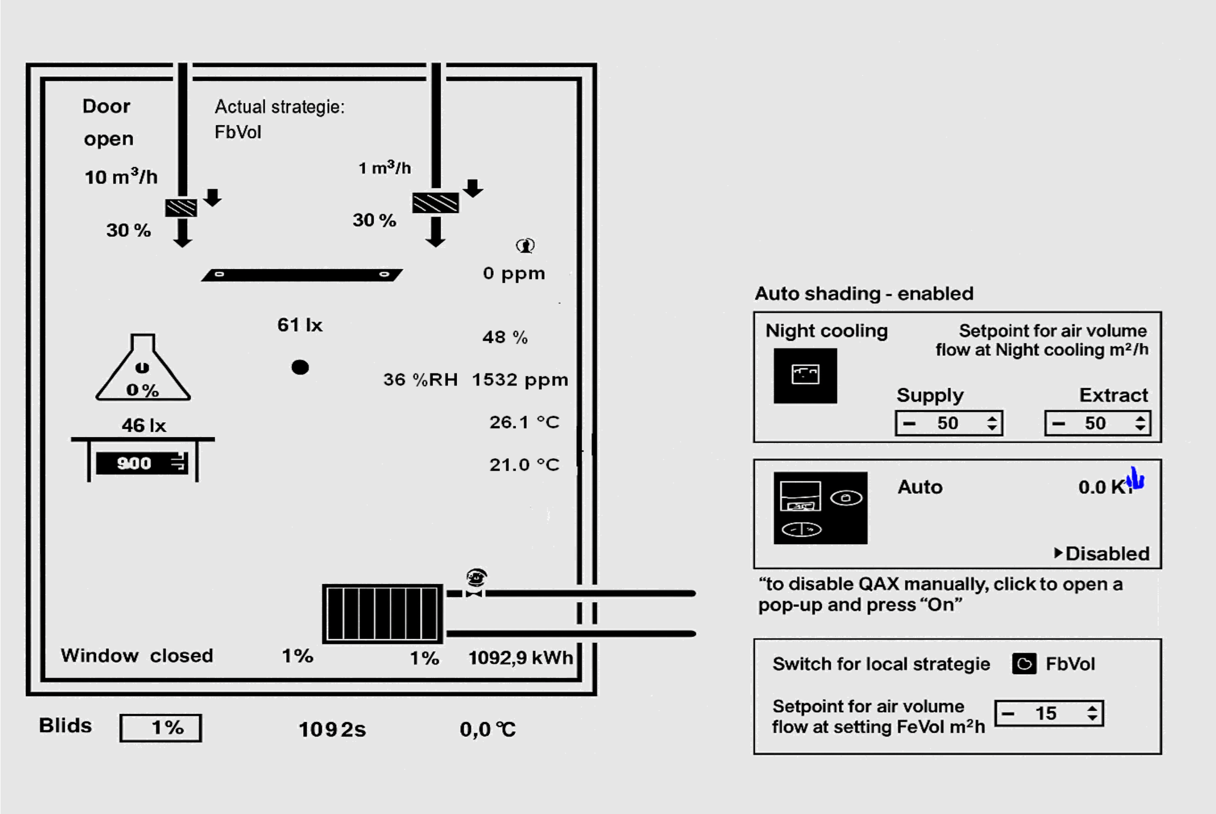


Fig. 3: Screen of the control system of the ventilation system – testbed air-handling unit setup control



Auto shading - enabled

Setpoint for air volume flow at Night cooling m²/h

Supply 50

Extract 50

"to disable QAX manually, click to open a pop-up and press "On"

Switch for local strategie FbVol

Setpoint for air volume flow at setting FeVol m²h 15

Fig. 4: Screen of the control system of the room – example for room R1 (A222). Rooms R2- R4 are equipped similarly.

3.2 Used air purifiers

Different types of air purifiers were strategically placed in three of the offices. The placement was carefully chosen to ensure that the purifiers were unobtrusive and did not interfere with the normal operation of the rooms. This thoughtful arrangement allowed the users to carry out their activities without any limitations, ensuring that the air purifiers could function effectively while maintaining a comfortable and practical workspace.

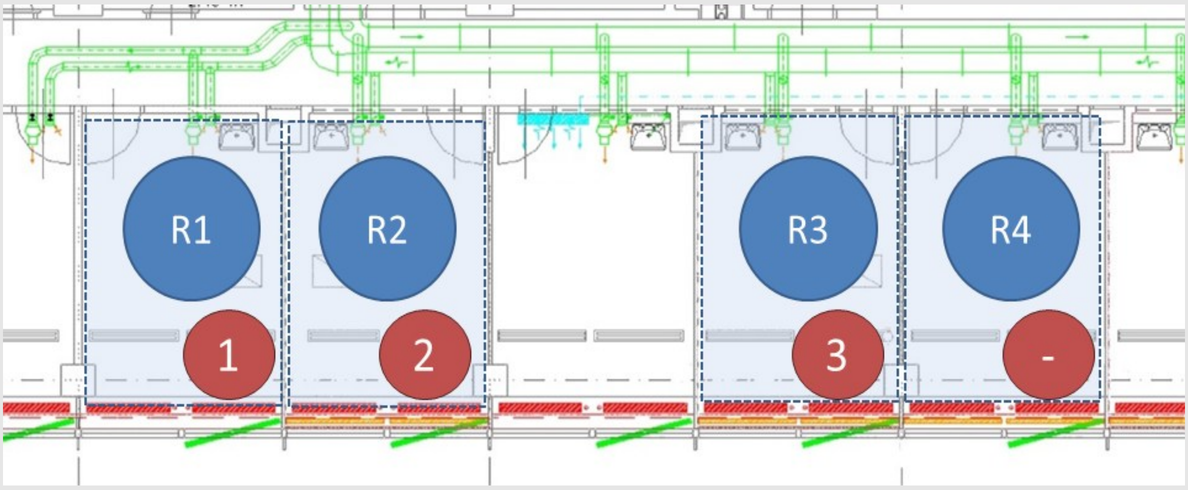


Fig. 5 Placement of air purifiers in rooms R1, R2, R3. Room R4 – Reference room without air purifier

Room R1 - Air purifier 1

The Ionic-Care Triton X6 is a combination air purifier and ionizer designed to improve indoor air quality. It features an electrostatic filter that effectively captures dust, pollen, and other airborne particles. The unit produces negatively charged ions. With a maximum airflow rate of 65 m^3/hr, it efficiently circulates and purifies the air in the room1. The Triton X6 operates quietly and has a low power consumption of just 8 watts.

Fig. 6 Air purifier 1

Room R2 - Air purifier 2

The Dyson Purifier Cool Gen1 TP10. It features a two-stage HEPA H13 filtration system that captures 99.97% of particles as small as 0,3 microns, including dust, allergens, and pollutants. Additionally, an activated carbon filter helps remove odors and gases, including volatile organic compounds (VOCs). Its maximum air flow rate is 1000 m^3/hr.

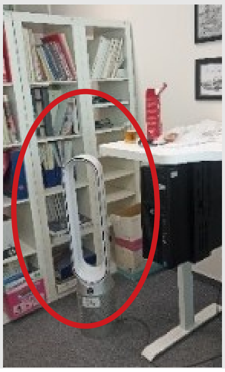


Fig. 7 Air purifier 2

Room R3 - Air purifier 3

Daikin Ururu MCK75JVM-K. Filtration system includes a streamer discharge unit, prefilter, plasma ionizer, electrostatic dust collection filter, and a Titanium apatite photocatalytic filter. This combination effectively captures and neutralizes dust, allergens, and other airborne pollutants. The unit has an adjustable airflow rate ranging from **60 to 420 cubic meters per hour.** It operates with a power consumption of 10 to 55 Watts.

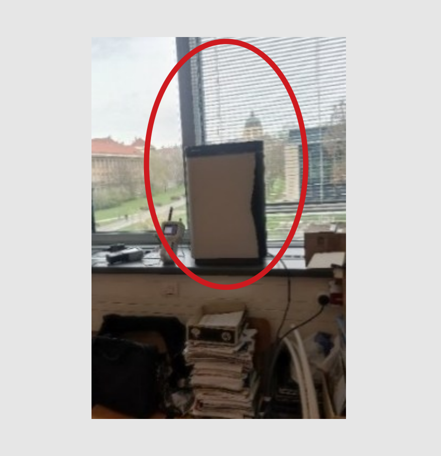


Fig. 8 **Air purifier 3**

Room R4 – no air purifier
Reference room without air purifier

Tab. 1 **Air purifiers parameters**

Parameter	Air purifier 1 Ionic-Care Triton X6 [33][34][35]	Air purifier 2 Dyson Purifier Cool Gen1 TP10 [36][37][38]	Air purifier 3 Daikin Ururu MCK75JVM-K [39][40][41]
Filtration Technology	Electrostatic washable filter with built-in ionizer	HEPA-13 filter, activated carbon filter	Electrostatic + Titanium apatite photocatalytic filter + Ionizer
Coverage Area	Up to 75 m²	Suitable for whole rooms (exact m² not specified)	Suitable for medium to large rooms
Noise Level	Max. 8 dB	Max. 61.4 dB	17 to 50 dB
Power Consumption	Max. 12 W	Max. 50 W	8 to 81 W
Airflow Rate	Up to 65 m³/h	Up to 1044 m³/h (290 l/s)	Up to 450 m³/h
Weight	3.2 kg	4.73 kg	11 kg
Dimensions (HxWxD)	71 x 25 x 21 cm	105 x 22 x 22 cm	59 x 39.5 x 26.8 cm
Additional Features	Silent operation, 3 performance modes, no filter replacements needed	Air Multiplier technology, remote control Cooling fan, LCD display	Humidifier function, child lock, timer
Ozone Emission	0.005 ppm	Not specified	Not specified
Filter Replacement	None (washable)	Every 12 months	Various intervals
Filtration Efficiency	96% (airborne contaminants)	99.97% (≥0.3 µm particles)	Not specified in sources

The experiment was divided into two distinct periods, separated by a four-month break. This break was strategically planned to wait for lower temperatures outside, ensuring a comprehensive analysis across different seasonal conditions. During each period, the researchers tested four different setups, making a total of eight setups over the entire study.

The first period spanned four weeks, during which each week was dedicated to testing a different air-cleaner setup. After the break, the second period followed the same pattern, with the same four setups being tested again under the new environmental conditions.

3.3 Monitored parameters and instruments used

A comprehensive set of parameters was meticulously monitored to assess the indoor environmental quality. These parameters included the supply air flow rate to the office, air temperature, humidity, and the concentrations of CO2, volatile organic compounds (VOC), formaldehyde, particulate matter (PM), and ozone. Additionally, questionnaires were administered to gather subjective feedback on the indoor environmental quality (IEQ) from the office users.

- **Comet Logger U4440M**: This device was employed to log various environmental parameters, ensuring accurate and reliable data collection over the study period.
- **Photoacoustic Gas Monitor Innova 1412 + 1303 Multipoint Sampler and Doser**: This sophisticated gas monitor, combined with a multipoint sampler and doser, was utilized to measure the concentrations of various gases, including CO_2, VOCs, and formaldehyde, with high precision.
- **Ozone Monitor WASP-XM**: This instrument was specifically used to monitor if any by-products were produced during the operation of the air purifiers, ensuring that the purification process did not introduce harmful ozone levels.

Each office user was asked to fill out an online questionnaire at least twice a week. These questionnaires contained numerous questions about their perception of different parameters of IEQ and their personal preferences. The Survio tool was used to facilitate this process.

3.4 Description of experiments

This experiment involves four rooms, each equipped with an adjustable ventilation system. The goal is to analyze the impact of different air flow rates on various environmental parameters. The experiment was conducted in three distinct setup modes, as detailed in the Tab. 1, below.

Tab. 2 **Ventilation rate setup**

Ventilation rate [m^3/h]	Room R1	Room R2	Room R3	Room R4
Setup 1	14	12	14	22
Setup 2	29	30	33	22

The experiment was conducted over nine weeks, with each week representing a different set of boundary conditions. See details in Tab. 2, below.

Tab. 3 **Experiments setup conditions**

Exp	Cleaner	Ventilation	Windows Door	From	To	Days
E1	ON	Setup 1	Closed	19.04.23 8:00	24.04.23 23:59	6
E2	ON	Setup 1	User	25.04.23 8:00	02.05.23 12:00	6
E3	ON – Placebo	Setup 1	Closed	03.05.23 8:00	09.05 23 12:00	7
E4	OFF	Setup 2	Closed	09.05.23 12:00	15.05.23 12:00	7
E6	OFF	Setup 2	Closed	18.12.23 8:00	22.12.23 23:59	5
E7	ON	Setup 1	Closed	8.1.24 8:00	12.1.24 23:59	5
E8	ON – Placebo	Setup 1	Closed	15.1.24 8:00	19.1.24 23:59	5
E9	ON – New filters	Setup 1	Closed	22.1.24 8:00	26.1.24 23:59	5

Note: E5 was not included in final evaluation due to nonstandard operation conditions

In fact the first phase (april-may 2023) of the experiment was running during spring 2023 and it was found out that the biggest issue is not the air quality but too high temperature in the rooms despite the fact that the users were allowed to open the windows to cool down the space when coming in the morning. So second additional phase followed during autumn/winter 2023/2024 (December-January).

Fig. 9 shows the outdoor air temperatures during the experiments, i.e., the daily minimum, maximum, and average temperatures measured by the nearest available weather station located 3.3 km from the measurement site.

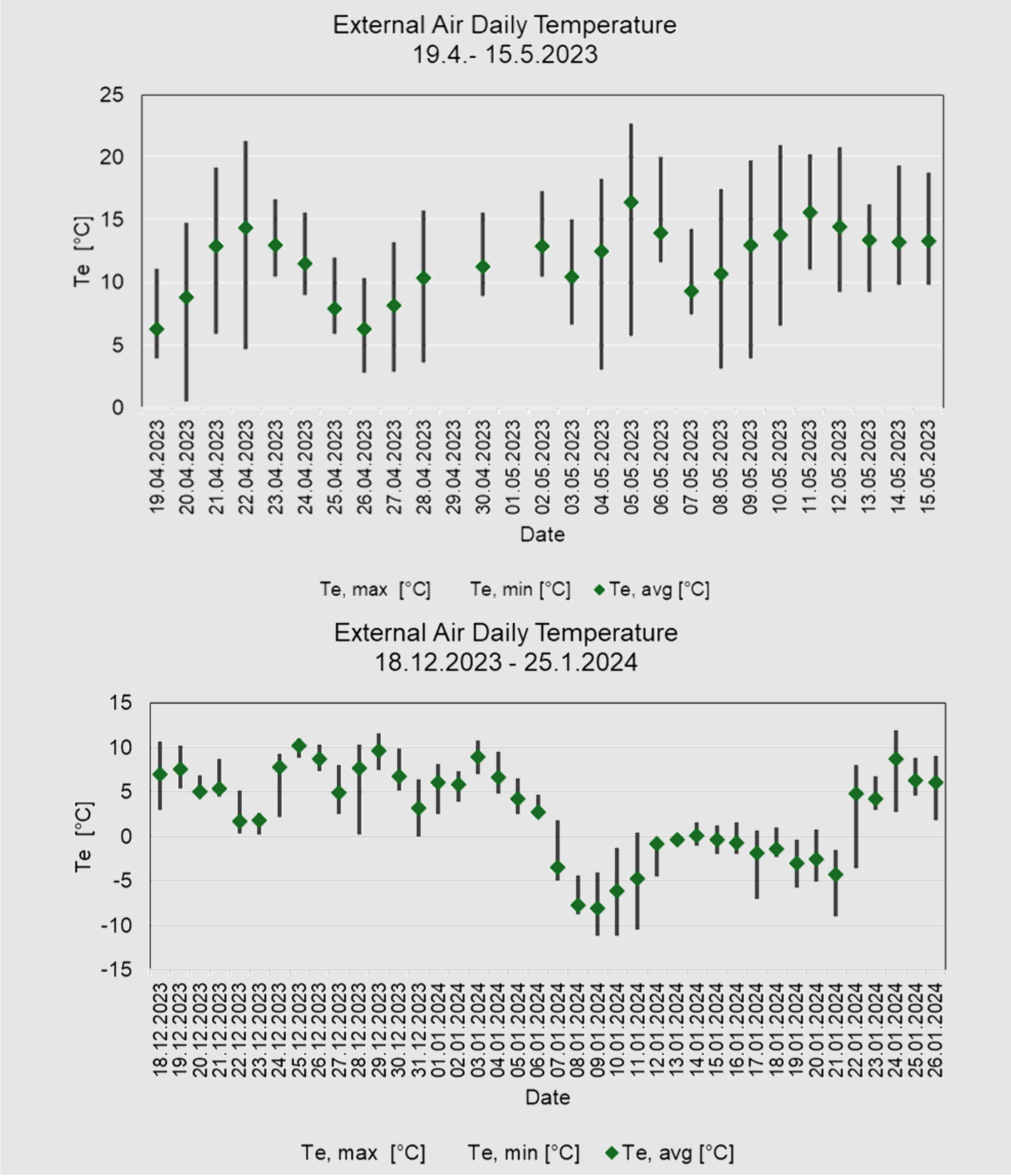


Fig. 9 Climate conditions during experiments (source: https://agropocasi.cz/meteostanice-czu/)

3.4.1 Air purifiers

The experiment involves the use of three air purifiers, each placed in a different room to analyze their impact on indoor air quality. Throughout the experiment, each air purifier remains in its designated room, except for one week before the start of Phase 2, when the purifiers are moved to different rooms. The air purifiers are operated under various modes to observe their effects. These modes include Auto Mode, where the purifier adjusts its settings automatically based on detected air quality; Maximum Mode, where the purifier operates at its highest capacity; Off Mode, where the purifier is turned off; and Placebo Mode, where the purifier runs without any filters, simulating operation without actual air purification.

In addition to the rooms with air purifiers, there is one more room being monitored where no air purifier is placed. This room serves as a control to compare the air quality against the rooms with purifiers.

In Phase 1, each air purifier is placed in its designated room and operated under the specified modes. One week before Phase 2, the air purifiers are moved to different rooms to observe the impact of changing their locations. In Phase 2, the air purifiers are returned to their original rooms and continue to operate under the specified modes.

The procedure involves initially setting up each air purifier in its designated room and ensuring it is functioning correctly. The purifiers are then operated under the specified modes according to the experimental schedule. During the pre-Phase 2 week, the air purifiers are moved to different rooms. Throughout the experiment, air quality parameters in each room, including the control room without a purifier, are monitored and recorded. The data collected is then analyzed to compare the effects of different modes and phases, determining the impact of air purifier settings and room changes.

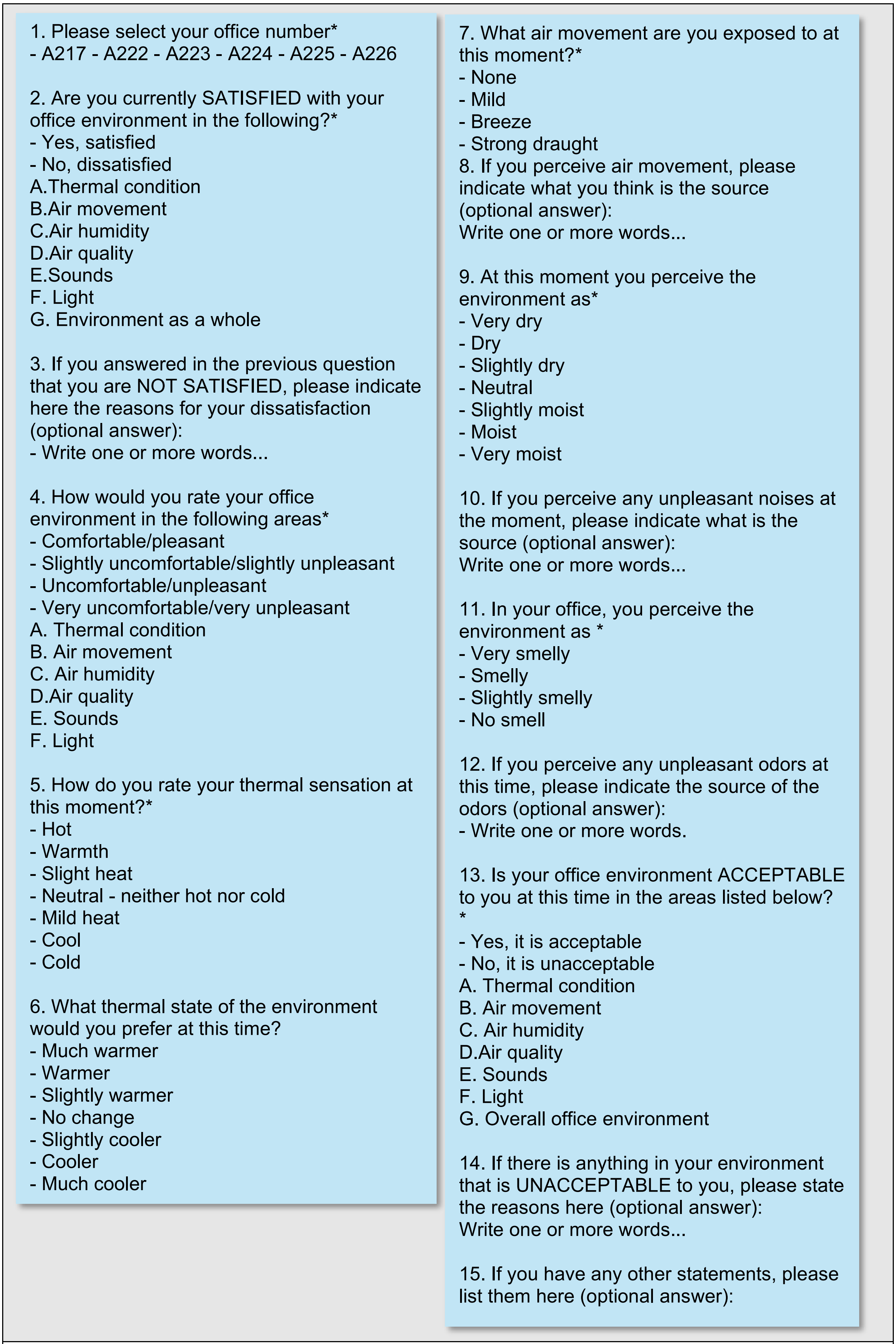
3.4.2 Operation mode of the room

The experiment included two distinct modes of room operation. These modes were designed to control the opening of windows and doors under different conditions.

In the User Mode, the opening of windows and doors was left to the discretion of the users. They could open or close the windows and doors as they wished throughout the day. In the Closed Mode, users were instructed to keep windows and doors closed throughout the day to maintain a controlled environment. However, they were allowed to open the windows briefly in the morning to cool down the space upon arrival. To ensure compliance, signs were placed on the doors and windows reminding users to keep them closed.

3.4.3 Questionnaires

During the experiment a comfort survey was conducted in the offices to gather feedback from users. The survey comprised 15 questions aimed at assessing various aspects of comfort, such as temperature, air quality, and overall satisfaction with the indoor environment. Four office users participated in the survey, providing a total of 78 responses. The survey was conducted online, 2-3 times during each phase of the experiment, ensuring that data was collected at multiple points to capture any changes in comfort levels. To encourage serious cooperation, participants were offered a reward for their valuable feedback. This incentive helped ensure that the responses were thoughtful and reflective of the users' true experiences. The survey aimed to capture real-time data on how different operation modes impacted the comfort levels of office users.



1. Please select your office number*
- A217 - A222 - A223 - A224 - A225 - A226

2. Are you currently SATISFIED with your office environment in the following?*
- Yes, satisfied
- No, dissatisfied

A.Thermal condition
B.Air movement
C.Air humidity
D.Air quality
E.Sounds
F. Light
G. Environment as a whole

3. If you answered in the previous question that you are NOT SATISFIED, please indicate here the reasons for your dissatisfaction (optional answer):
- Write one or more words...

4. How would you rate your office environment in the following areas*
- Comfortable/pleasant
- Slightly uncomfortable/slightly unpleasant
- Uncomfortable/unpleasant
- Very uncomfortable/very unpleasant

A. Thermal condition
B. Air movement
C. Air humidity
D.Air quality
E. Sounds
F. Light

5. How do you rate your thermal sensation at this moment?*
- Hot
- Warmth
- Slight heat
- Neutral - neither hot nor cold
- Mild heat
- Cool
- Cold

6. What thermal state of the environment would you prefer at this time?
- Much warmer
- Warmer
- Slightly warmer
- No change
- Slightly cooler
- Cooler
- Much cooler

7. What air movement are you exposed to at this moment?*
- None
- Mild
- Breeze
- Strong draught

8. If you perceive air movement, please indicate what you think is the source (optional answer):
Write one or more words...

9. At this moment you perceive the environment as*
- Very dry
- Dry
- Slightly dry
- Neutral
- Slightly moist
- Moist
- Very moist

10. If you perceive any unpleasant noises at the moment, please indicate what is the source (optional answer):
Write one or more words...

11. In your office, you perceive the environment as *
- Very smelly
- Smelly
- Slightly smelly
- No smell

12. If you perceive any unpleasant odors at this time, please indicate the source of the odors (optional answer):
- Write one or more words.

13. Is your office environment ACCEPTABLE to you at this time in the areas listed below?
*
- Yes, it is acceptable
- No, it is unacceptable

A. Thermal condition
B. Air movement
C. Air humidity
D.Air quality
E. Sounds
F. Light
G. Overall office environment

14. If there is anything in your environment that is UNACCEPTABLE to you, please state the reasons here (optional answer):
Write one or more words...

15. If you have any other statements, please list them here (optional answer):

Fig. 10 Questionnaire

4. Results

The results were processed separately for each room, combined into a single graph for all experiments (E1-E9) for the respective concentration of the monitored compound/parameter. In the graphs, experiments with similar setups are displayed together, thus they do not correspond sequentially to numbers 1-9. Working hours from 8 a.m. to 7 p.m. Monday to Friday were always considered for the evaluation. For each experiment were chosen 3 typical days.

Tab. 4 Summary of experiments

Experiment	Equipment status
E1, E7, E9	Air purifier on, closed windows, doors, lower air change rate
E2	Air purifier on, windows/doors according to user, lower air change rate
E4, E6	Air purifier off , closed windows, doors, higher air change rate
E3, E8	Placebo - air purifier off or without filters, lower air change rate

Tab. 5 Conversion between numerical and verbal IEQ evaluation (for graphs)

Assesment criterion		Numerical assessment						
		-3	**-2**	**-1**	**0**	**1**	**2**	**3**
Thermal comfort	**Heat sensation**	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
	Preferences	Much cooler	Cooler	Slightly cooler	No change	Slightly warmer	warmer	Much warmer
	Comfort	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Rather comfortable	Comfortable
	Satisfaction	Dissatisfied	Rather dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Rather satisfied	Satisfied
	Acceptability	Unacceptable	Rather unacceptable	Slightly unacceptable	Neutra	Slightly acceptable	Rather acceptable	Acceptable
IAQ	**Odour**	Strongly odorous	Odorous	Slightly odorous	Odorless	x	x	x
	Comfort	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Rather comfortable	Comfortable
	Satisfaction	Dissatisfied	Rather dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Rather satisfied	Satisfied
	Acceptability	Unacceptable	Rather unacceptable	Slightly unacceptable	Neutral	Slightly acceptable	Rather acceptable	Acceptable
Air movement	**Movement**	Strong draught	Draught	Slight draught	No air movement	x	x	x
	Comfort	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Rather comfortable	Comfortable
	Satisfaction	Dissatisfied	Rather dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Rather satisfied	Satisfied
	Acceptability	Unacceptable	Rather unacceptable	Slightly unacceptable	Neutral	Slightly acceptable	Rather acceptable	Acceptable
Hum	**Humidity**	Very dry	Dry	Slightly dry	Neutral	Slightly humid	Humid	Very humid

	Comfort	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Rather comfortable	Comfortable
	Satisfaction	Dissatisfied	Rather dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Rather satisfied	Satisfied
	Acceptability	Unacceptable	Rather unacceptable	Slightly unacceptable	Neutral	Slightly acceptable	Rather acceptable	Acceptable
Noise	**Comfort**	Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Rather comfortable	Comfortable
	Satisfaction	Dissatisfied	Rather dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Rather satisfied	Satisfied
	Acceptability	Unacceptable	Rather unacceptable	Slightly unacceptable	Neutral	Slightly acceptable	Rather acceptable	Acceptable

4.1 Room R1 – Air purifier 1

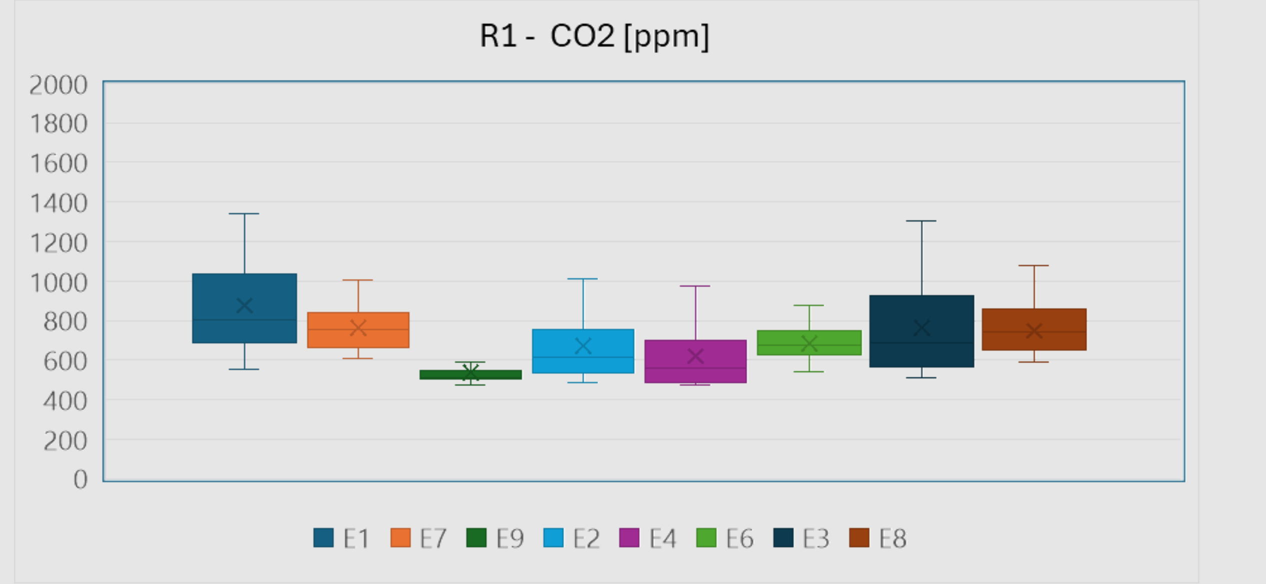


Fig. 11 Room 1 – CO_2 concentration statistic during working hours E1- E8 experiments (see tab 3)

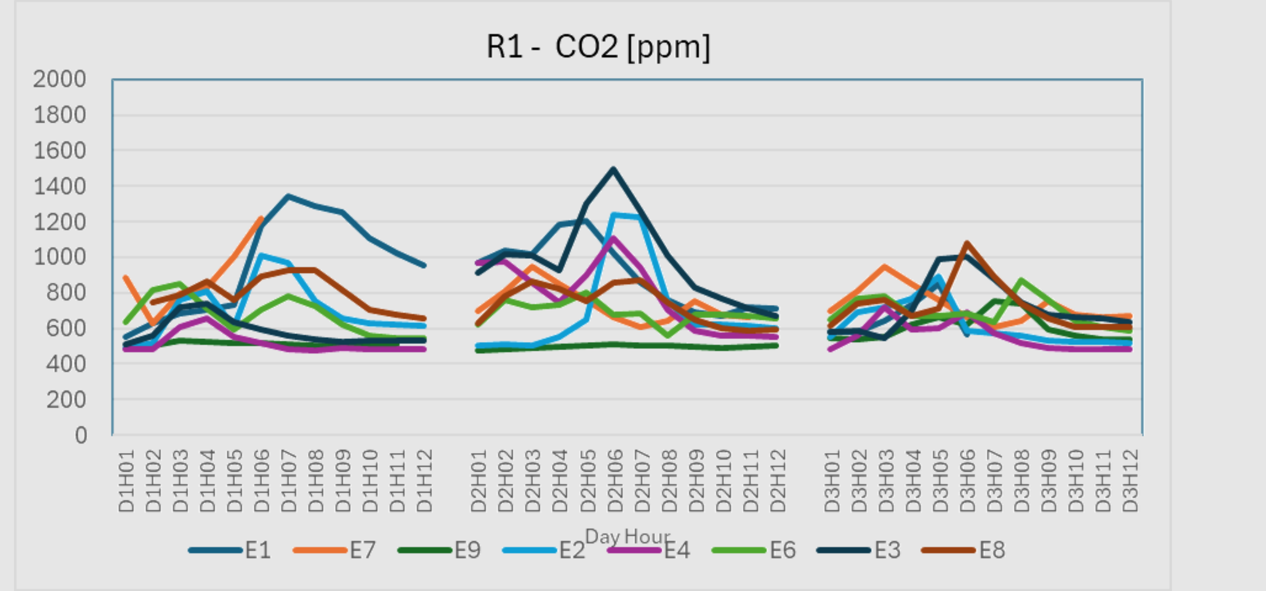


Fig. 12 Room 1 – CO_2 concentration during working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 6 Room 1 – CO_2 concentration statistic during working hours

R1 - CO_2 [ppm]	**Experiment**							
	E1	E7	E9	E2	E4	E6	E3	E8
Min	555,11	606,84	476,42	487,15	475,33	544,26	512,87	589,54
Max	1341,04	1220,16	756,33	1237,10	1109,46	873,97	1495,23	1079,90
Mean	875,34	764,62	539,55	673,04	620,88	684,47	765,14	748,44
Standard Deviation	238,80	137,19	66,48	185,38	171,13	83,37	239,85	117,86
Quartile 1	683,13	663,91	501,69	536,34	485,32	625,94	566,69	650,42
Quartile 2	806,08	752,06	511,14	616,16	557,68	676,03	688,32	745,36
Quartile 3	1057,10	840,30	546,17	753,00	702,52	750,98	922,86	858,76

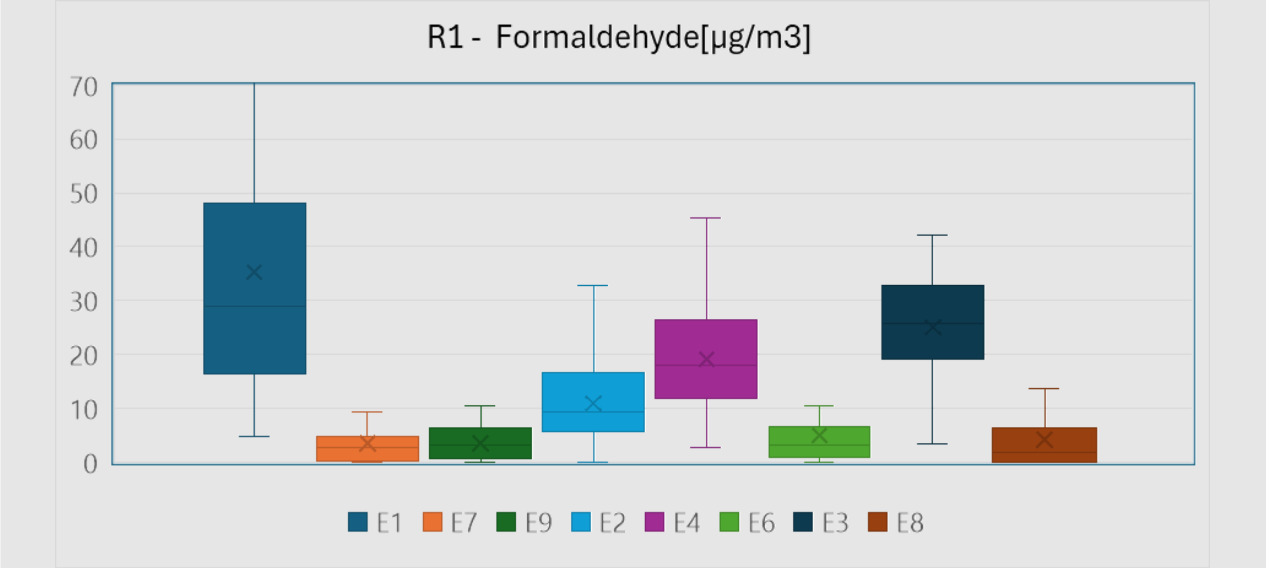


Fig. 13 Room 1 – Formaldehyde concentration statistic during working hours E1- E8 experiments (see tab 3)

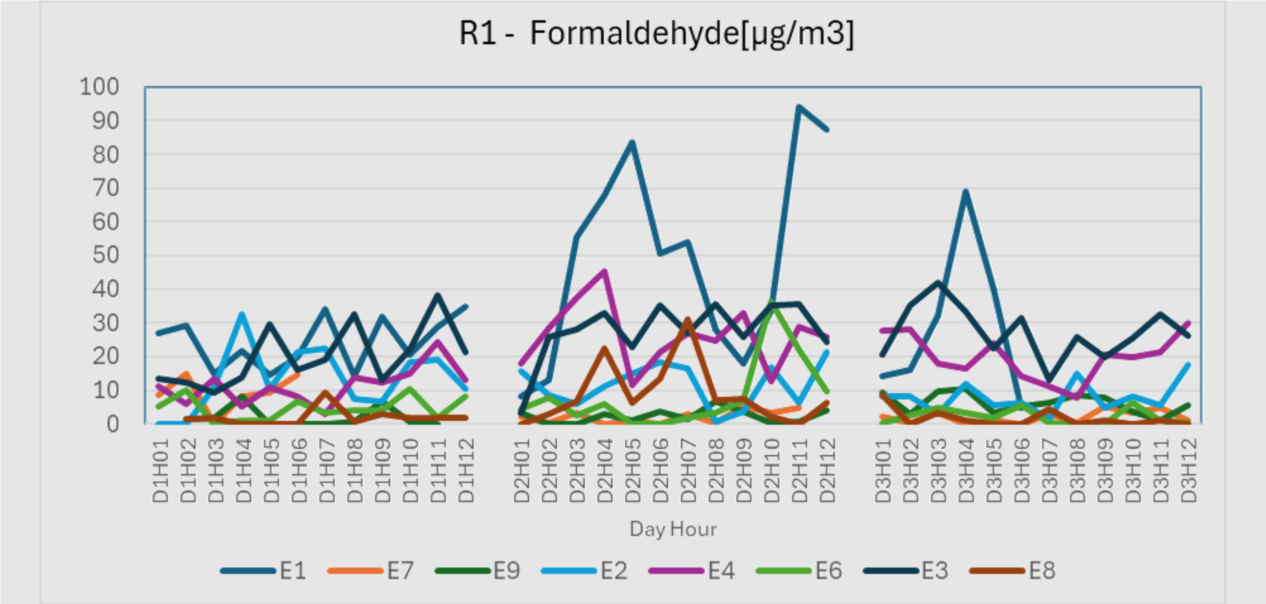


Fig. 14 Room1 Formaldehyde concentration during working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 7 Room 1 – Formaldehyde concentration statistic during working hours

R1 - Formaldehyde [µg/m3]	**Experiment**							
	E1	E7	E9	E2	E4	E6	E3	E8
Min	4,66	0,00	0,00	0,00	2,74	0,00	3,44	0,00
Max	94,09	14,93	10,43	32,72	45,24	36,48	42,10	30,86
Mean	35,35	3,49	3,50	10,94	19,10	5,05	25,01	4,18
Standard Deviation	23,90	4,00	3,20	7,34	9,45	6,85	9,06	6,52
Quartile 1	15,63	0,25	0,65	5,67	11,78	0,86	19,05	0,00
Quartile 2	28,92	2,82	3,07	9,36	17,94	3,28	25,85	1,71
Quartile 3	51,43	4,88	6,31	16,71	26,53	6,53	32,92	6,36

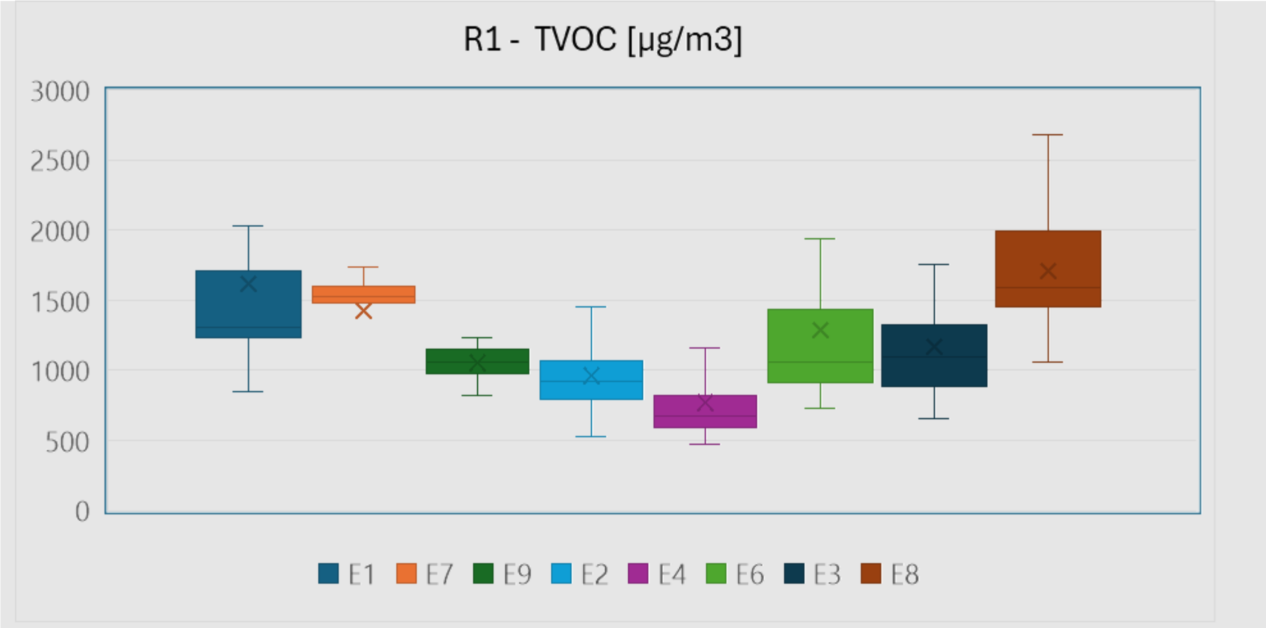


Fig. 15 Room 1 – TVOC concentration statistic during working hours E1- E8 experiments (see tab 3)

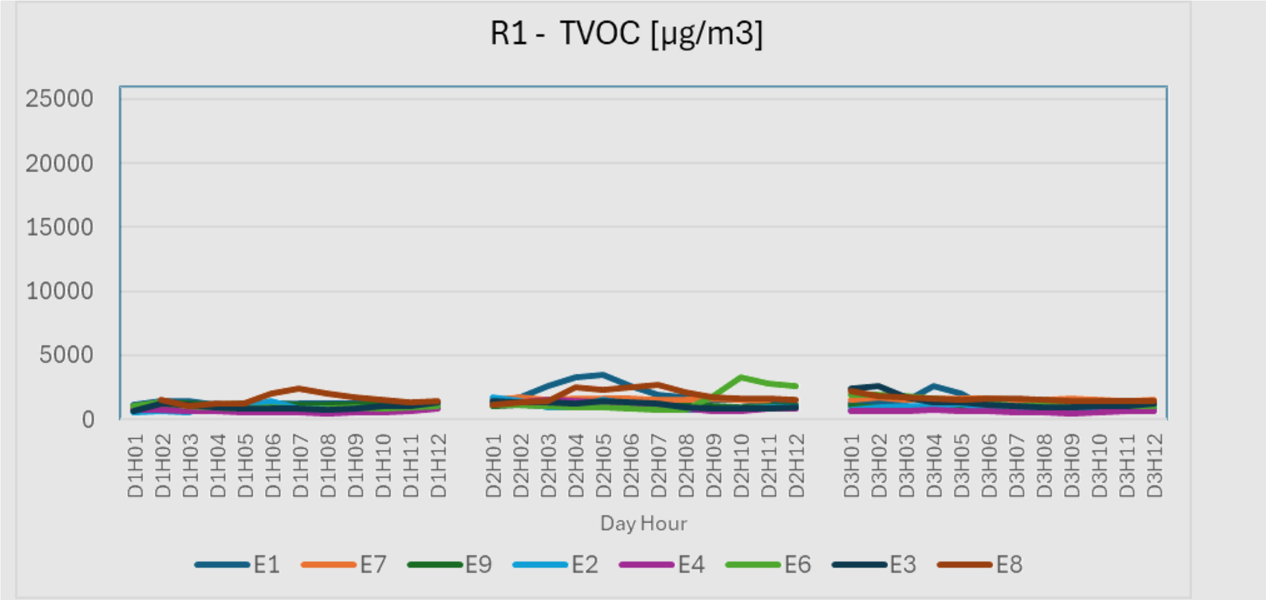


Fig. 16 Room1 TVOC concentration during working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 8 Room 1 – TVOC concentration statistic during working hours

R1 - TVOC [µg/m3]	Experiment							
	E1	E7	E9	E2	E4	E6	E3	E8
Min	847,60	734,38	817,87	531,01	471,80	727,70	657,47	1055,24
Max	3438,26	1732,52	1234,31	1746,39	1495,22	3273,01	2585,91	2674,84
Mean	1618,45	1427,21	1054,63	963,47	769,56	1289,94	1170,69	1707,67
Standard Deviation	645,22	284,11	105,54	258,76	269,99	586,72	393,01	404,20
Quartile 1	1234,70	1477,03	976,27	795,52	594,46	913,23	885,69	1453,06
Quartile 2	1303,12	1526,86	1055,82	925,76	673,69	1060,15	1091,73	1588,59
Quartile 3	1775,58	1600,74	1151,41	1064,25	822,48	1438,47	1326,13	1994,98

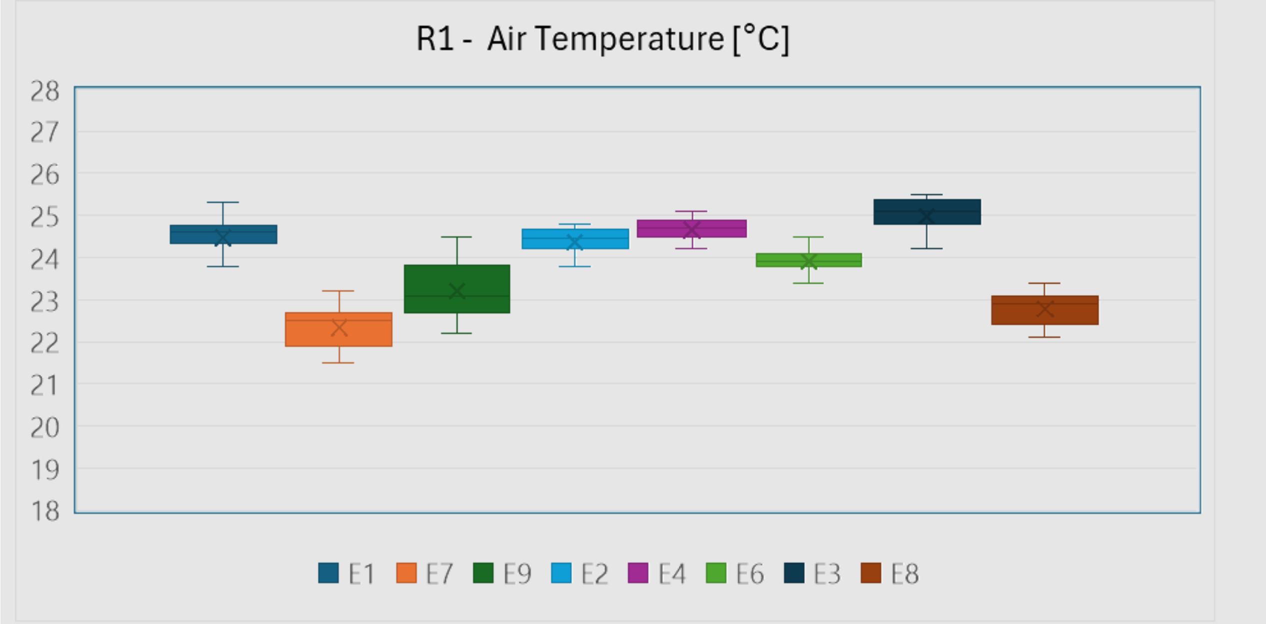


Fig. 17 Room 1 – Air temperature statistic during working hours E1- E8 experiments (see tab 3)

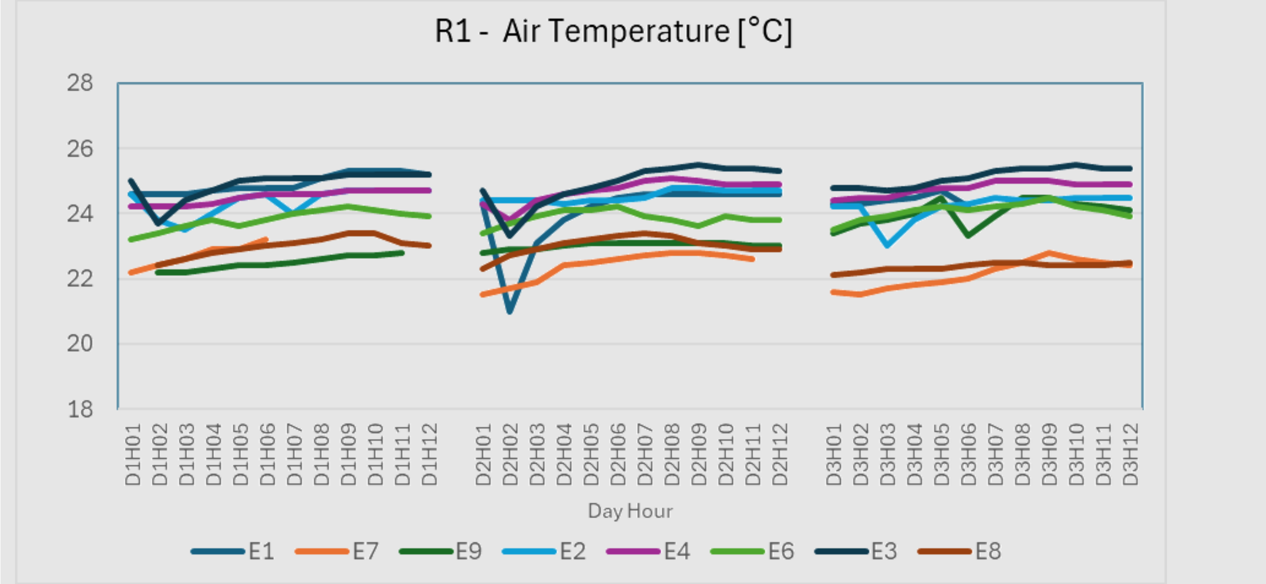


Fig. 18 Room1 Air temperature during working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 9 Room 1 – Air temperature concentration statistic during working hours

R1 - Air Temperature [°C]				Experiment				
	E1	E7	E9	E2	E4	E6	E3	E8
Min	21,00	21,50	22,20	23,00	23,80	23,20	23,30	22,10
Max	25,30	23,20	24,50	24,80	25,10	24,50	25,50	23,40
Mean	24,47	22,34	23,21	24,37	24,66	23,91	24,98	22,78
Standard Deviation	0,78	0,46	0,69	0,37	0,29	0,28	0,48	0,39
Quartile 1	24,30	21,90	22,70	24,23	24,50	23,80	24,80	22,40
Quartile 2	24,60	22,50	23,10	24,45	24,70	23,90	25,10	22,90
Quartile 3	24,80	22,70	23,83	24,68	24,90	24,10	25,38	23,10

Tab. 10 Room 1 – Summary of questionnaire - verbal

R1		E1	E7	E9	E2	E4	E6	E3	E8
Thermal comfort	Heat sensation	Warm	Neutral	Slightly warm	Warm	Hot	Warm	Hot	Slightly warm
	Preferences	Slightly cooler	No change	Slightly cooler	Cooler	Much cooler	Cooler	Much cooler	Slightly cooler
	Comfort	Slightly uncomfortable	Comfortable	Slightly uncomfortable	Uncomfortable	Very uncomfortable	Uncomfortable	Very uncomfortable	Slightly uncomfortable
	Satisfaction	N/A	Satisfied	Dissatisfied	Slightly dissatisfied	Dissatisfied	Dissatisfied	Dissatisfied	N/A
	Acceptability	Acceptable	Acceptable	Acceptable	Slightly unacceptable	Unacceptable	Unacceptable	Unacceptable	Acceptable
IAQ	Odour	Odorless	Odorless	Odorless	Slightly odorous	Odorless	Slightly odorous	Odorless	Slightly odorous
	Comfort	Slightly comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Slightly uncomfortable
	Satisfaction	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Dissatisfied
	Acceptability	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	N/A
Air movement	Movement	No air movement	No air movement	No air movement	No air movement	No air movement	No air movement	No air movement	No air movement
	Comfort	Comfortable	Comfortable	Slightly uncomfortable	Comfortable	Very uncomfortable	Slightly uncomfortable	Very uncomfortable	Slightly uncomfortable
	Satisfaction	Satisfied	Satisfied	Dissatisfied	Satisfied	Dissatisfied	Dissatisfied	Dissatisfied	Satisfied
	Acceptability	Acceptable	Acceptable	Acceptable	Acceptable	Unacceptable	Slightly unacceptable	Unacceptable	Acceptable
Humidity	Humidity	Slightly dry	Dry	Dry	Dry	Slightly dry	Dry	Very dry	Dry
	Comfort	Slightly uncomfortable	Slightly uncomfortable	Slightly uncomfortable	Slightly uncomfortable	Uncomfortable	Slightly uncomfortable	Uncomfortable	Uncomfortable
	Satisfaction	Dissatisfied	Dissatisfied	Dissatisfied	Slightly dissatisfied	Dissatisfied	Dissatisfied	Dissatisfied	Dissatisfied
	Acceptability	Acceptable	N/A	Acceptable	Acceptable	N/A	Unacceptable	Slightly acceptable	Unacceptable
Noise	Comfort	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable	Comfortable
	Satisfaction	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable

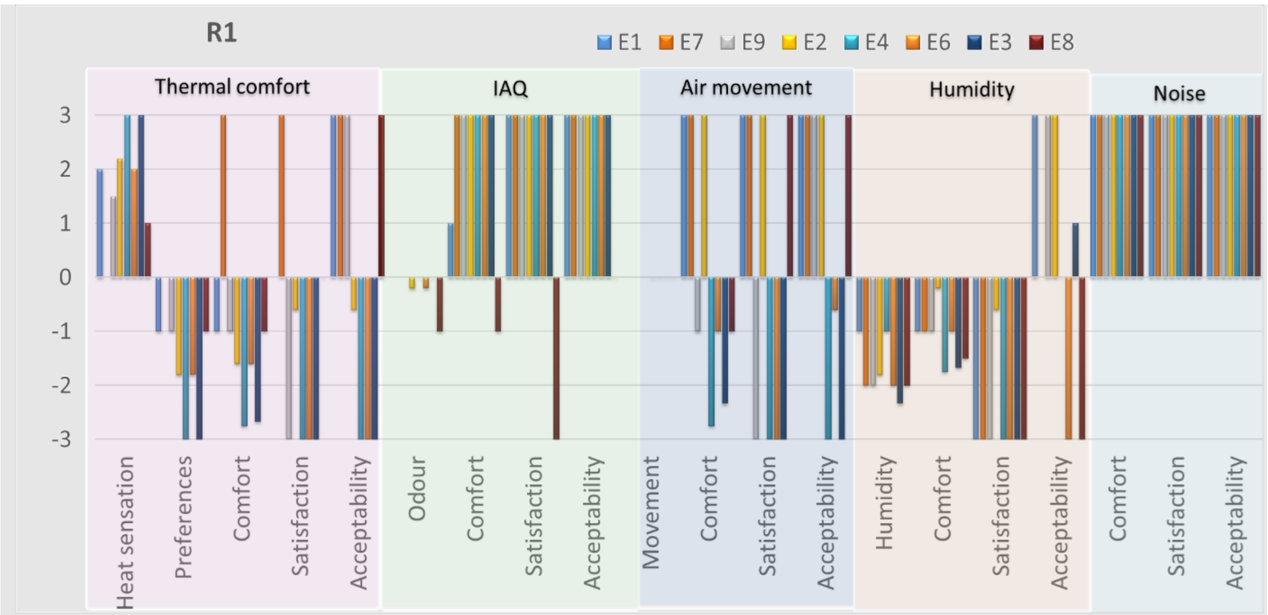


Fig. 19 Room 1 – Summary of questionnaire – numerical (see table 5)

4.2 Room R2 – Air purifier 2

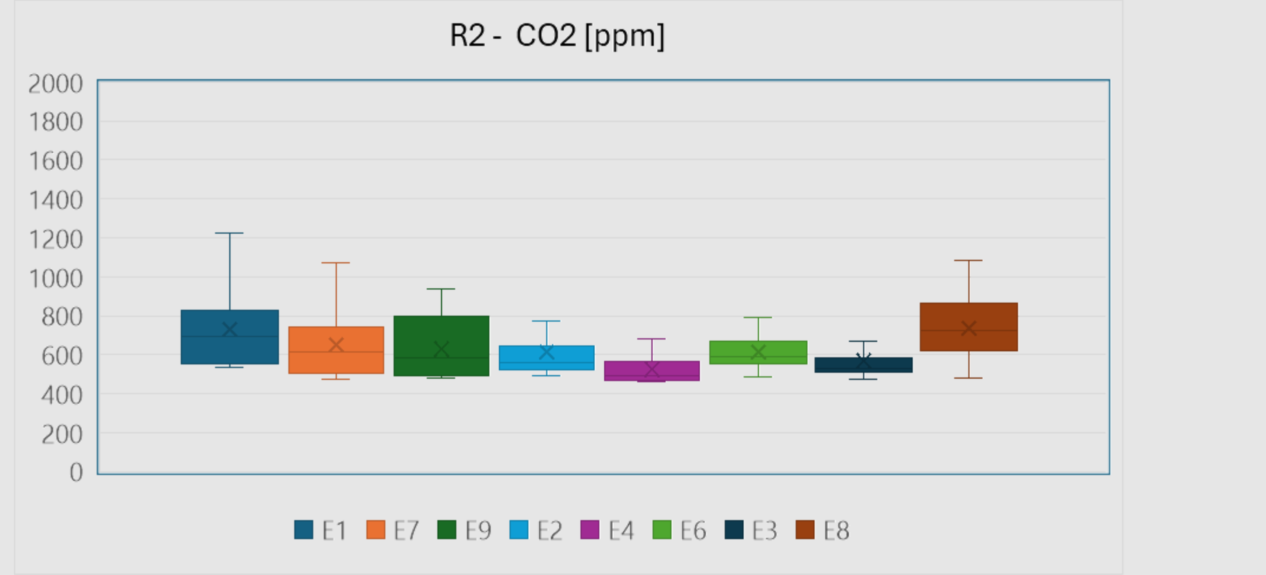


Fig. 20 Room 2 – CO_2 concentration statistic during working hours E1- E8 experiments (see tab 3)

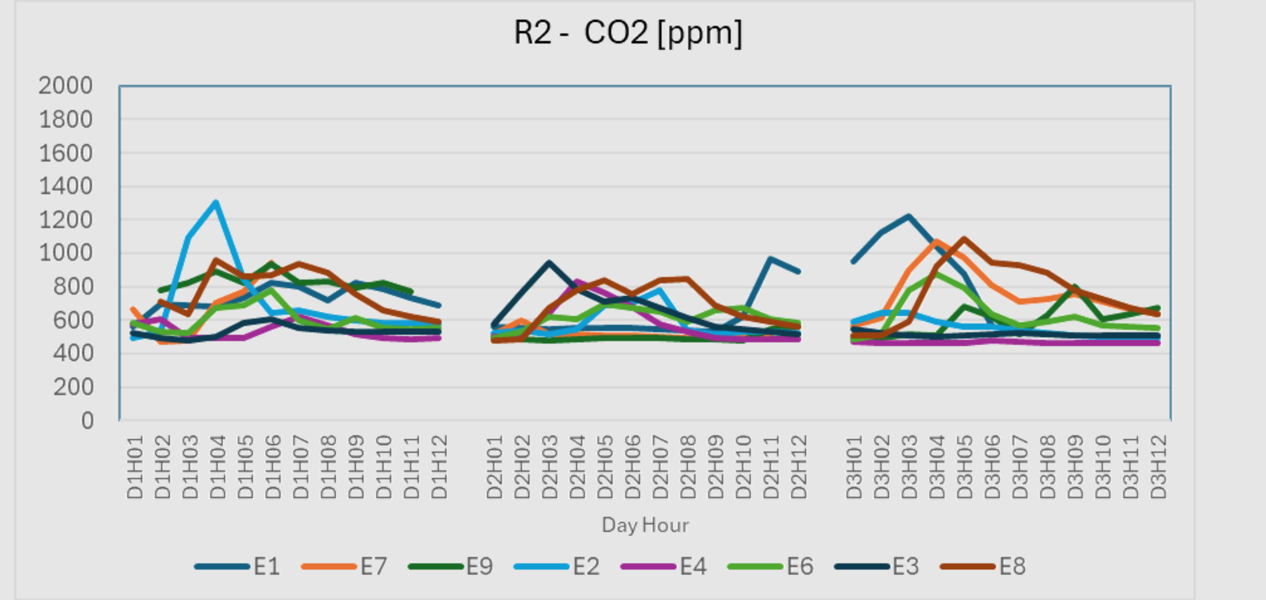


Fig. 21 Room 2 – CO_2 concentration working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 11 Room 2 – CO_2 concentration statistic during working hours

R2 - CO_2 [ppm]	**Experiment**							
	E1	E7	E9	E2	E4	E6	E3	E8
Min	534,51	472,36	480,95	493,34	459,75	489,01	475,64	477,38
Max	1223,96	1071,96	939,24	1300,94	832,84	878,10	945,74	1082,79
Mean	731,60	649,60	631,01	614,20	526,95	614,18	569,78	737,10
Standard Deviation	186,82	164,38	149,17	163,31	86,48	87,72	99,46	154,21
Quartile 1	554,95	505,13	490,38	524,37	468,22	551,44	510,84	618,57
Quartile 2	692,56	614,75	585,60	560,60	490,13	592,23	528,43	724,28
Quartile 3	838,40	743,33	795,37	643,73	565,82	669,35	584,48	866,08

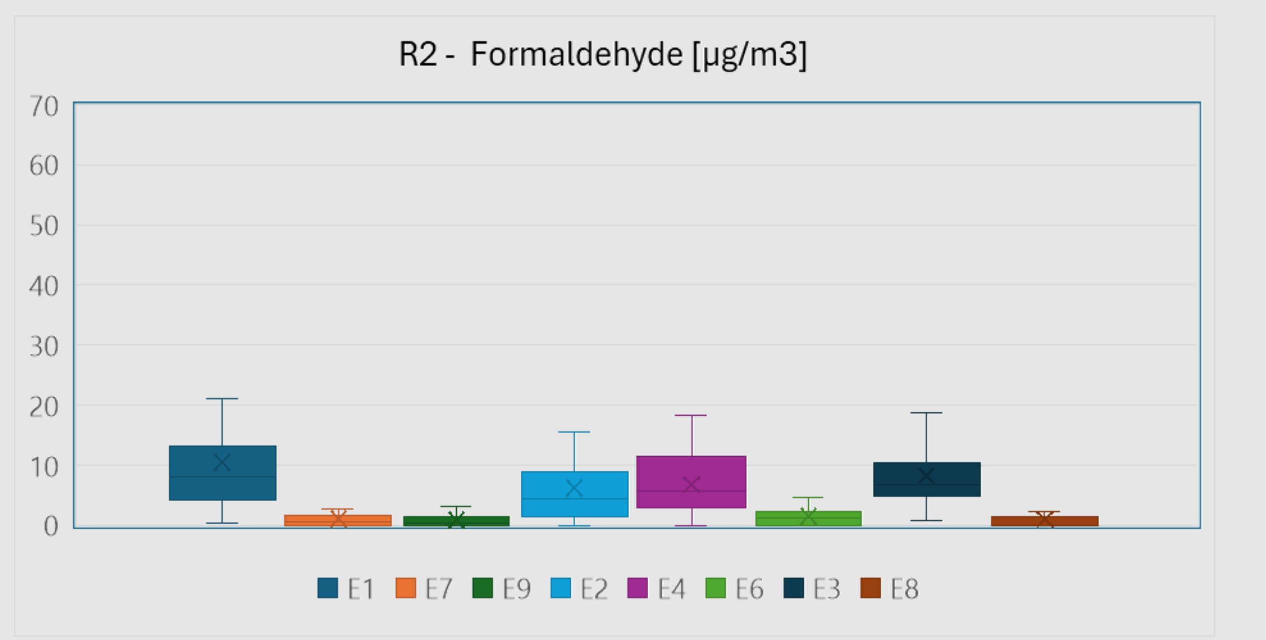


Fig. 22 Room 2 – Formaldehyde concentration statistic during working hours E1- E8 experiments (see tab 3)

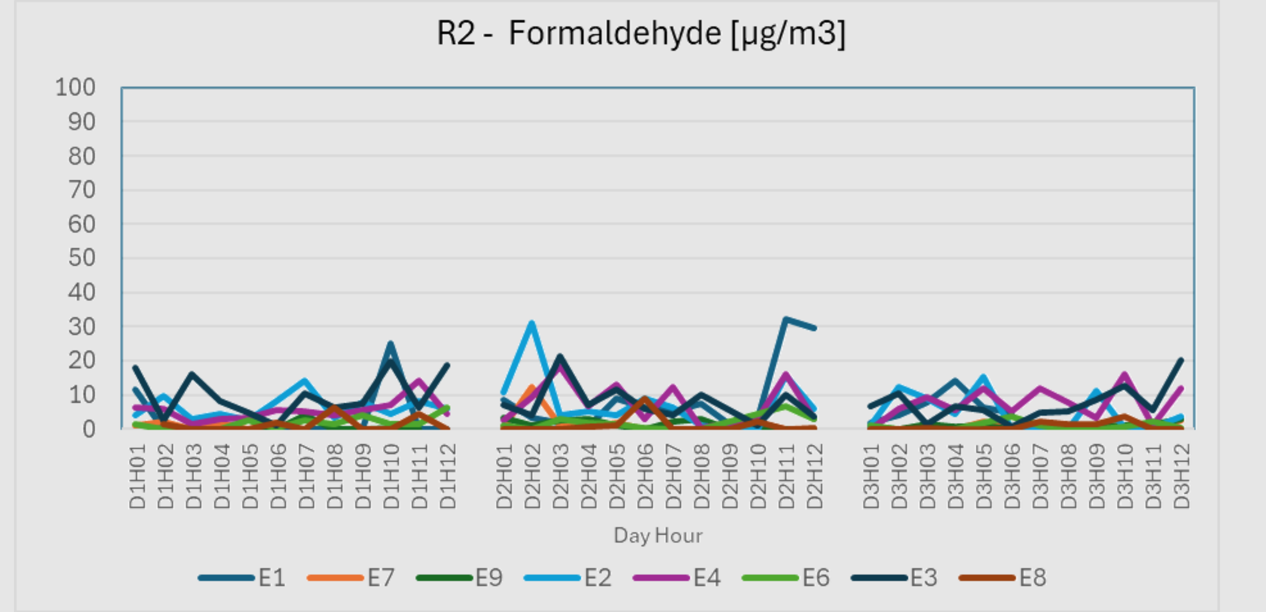


Fig. 23 Room 2 – Formaldehyde concentration working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 12 Room 2 – Formaldehyde concentration statistic during working hours

R2 - Formaldehyde [µg/m3]			**Experiment**					
	E1	E7	E9	E2	E4	E6	E3	E8
Min	0,46	0,00	0,00	0,00	0,00	0,00	0,79	0,00
Max	32,09	12,45	4,09	31,09	18,21	6,73	21,31	9,00
Mean	10,53	1,11	0,90	6,27	6,79	1,56	8,28	1,03
Standard Deviation	8,51	2,30	1,14	6,12	4,79	1,72	5,60	1,98
Quartile 1	3,74	0,00	0,00	1,43	2,91	0,00	4,80	0,00
Quartile 2	8,02	0,51	0,43	4,39	5,60	1,21	6,73	0,00
Quartile 3	13,43	1,70	1,33	8,92	11,37	2,29	10,46	1,35

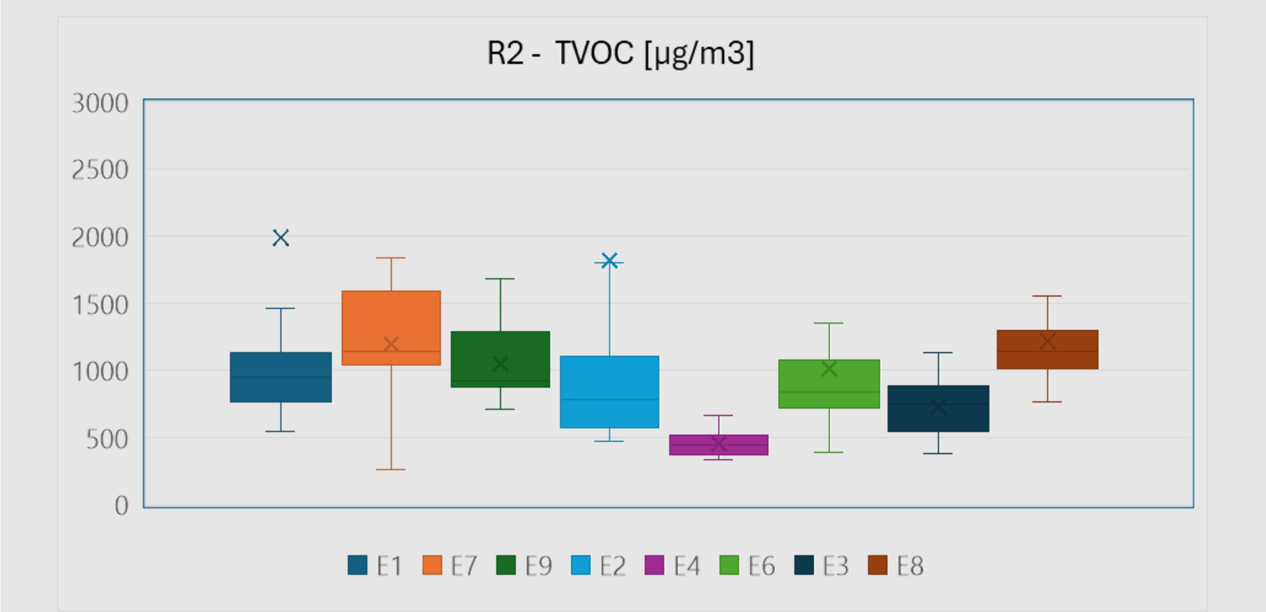


Fig. 24 Room 2 – TVOC concentration statistic during working hours E1- E8 experiments (see tab 3)

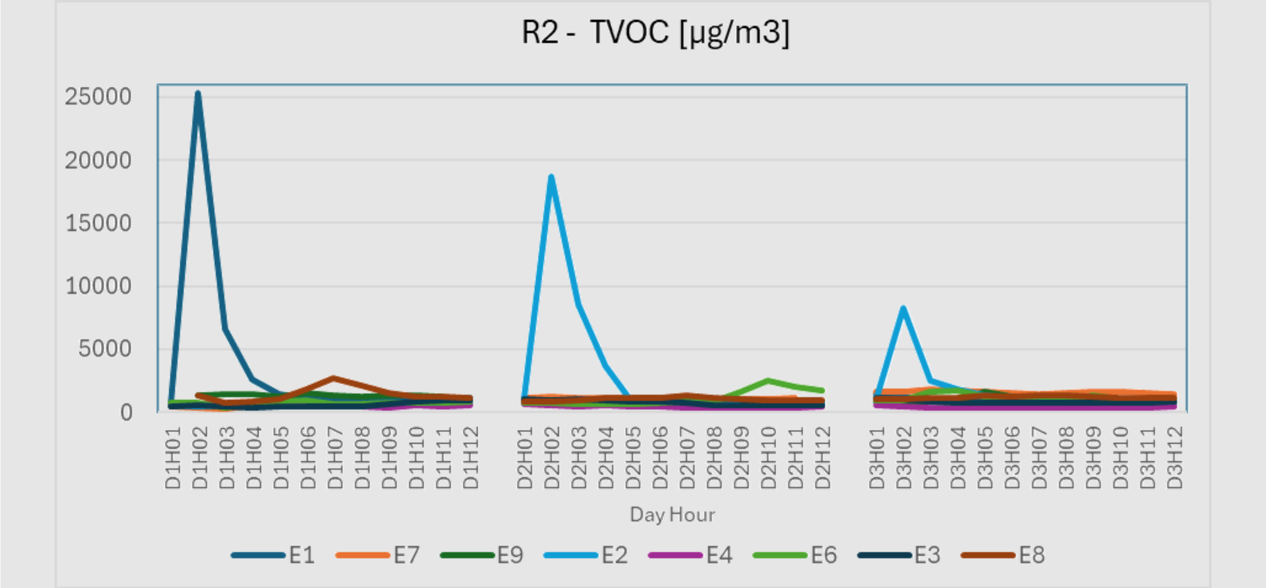


Fig. 25 Room 2 – TVOC concentration working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 13 Room 2 – TVOC concentration statistic during working hours

R2 - TVOC [µg/m^3]	**Experiment**							
	E1	E7	E9	E2	E4	E6	E3	E8
Min	545,52	259,77	713,28	474,39	331,83	388,28	379,35	769,32
Max	25350,73	1835,65	1680,08	18661,33	661,87	2550,16	1130,42	2718,21
Mean	1987,40	1194,11	1051,37	1819,60	453,73	1013,10	727,22	1217,95
Standard Deviation	4471,57	428,44	253,70	3382,19	93,54	446,84	200,68	364,67
Quartile 1	759,77	1042,54	872,51	574,55	370,21	724,07	543,13	1013,30
Quartile 2	944,67	1140,91	919,69	783,79	444,04	837,44	751,64	1141,00
Quartile 3	1141,60	1585,57	1284,95	1102,58	523,23	1074,36	883,40	1295,55

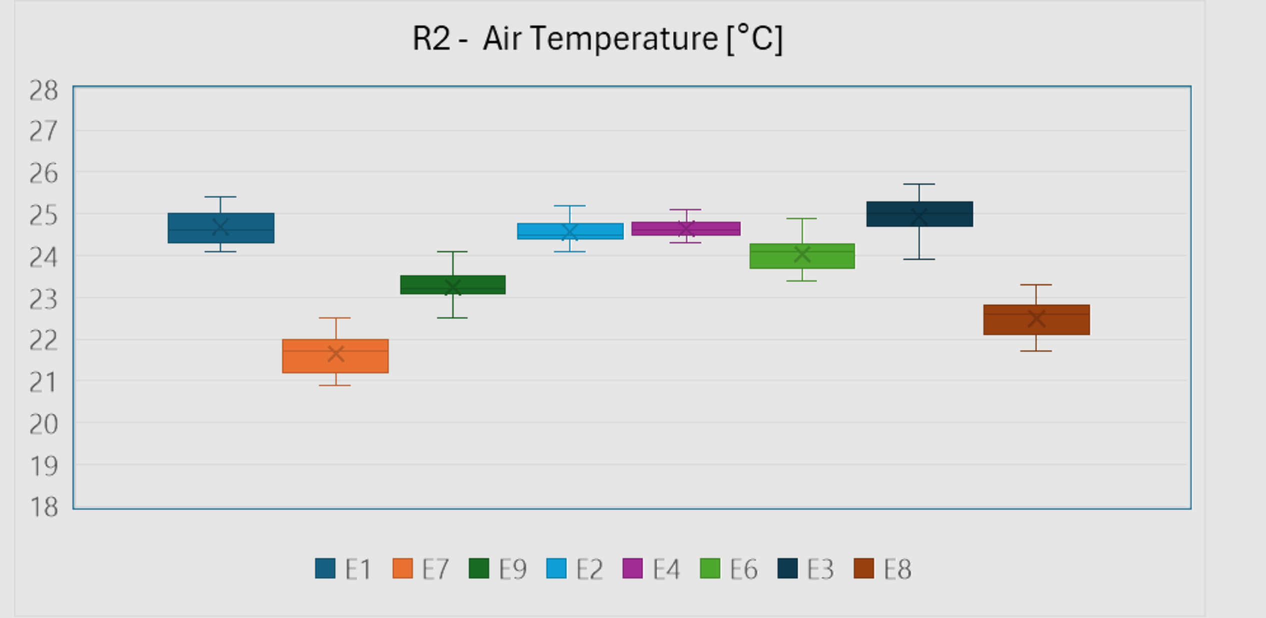


Fig. 26 Room 2 – Air temperature statistic during working hours E1- E8 experiments (see tab 3)

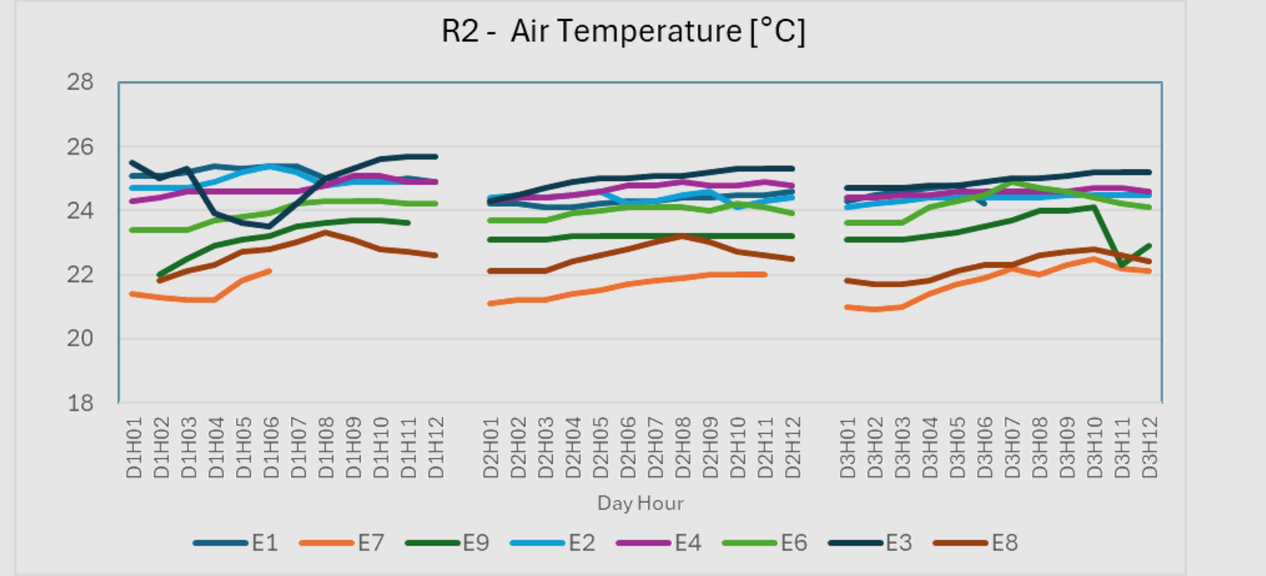


Fig. 27 Room 2 – T Air temperature working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 14 Room 2 – Air temperature statistic during working hours

R2 - Air Temperature [°C]			**Experiment**					
	E1	E7	E9	E2	E4	E6	E3	E8
Min	24,10	20,90	22,00	24,10	24,30	23,40	23,50	21,70
Max	25,40	22,50	24,10	25,40	25,10	24,90	25,70	23,30
Mean	24,68	21,66	23,24	24,57	24,65	24,03	24,93	22,49
Standard Deviation	0,42	0,44	0,43	0,30	0,20	0,36	0,51	0,43
Quartile 1	24,30	21,20	23,10	24,40	24,50	23,70	24,70	22,10
Quartile 2	24,60	21,70	23,20	24,50	24,60	24,10	25,00	22,60
Quartile 3	25,03	22,00	23,53	24,78	24,80	24,28	25,28	22,80

Tab. 15 Room 2 – Summary of questionnaire - verbal

R 2		E1	E7	E9	E2	E4	E6	E3	E8
Thermal comfort	**Heat sensation**	Hot	No data	Hot	Warm	Warm	Hot	No data	Warm
	Preferences	Slightly cooler	No data	Much cooler	Slightly cooler	Cooler	Cooler	No data	Cooler
	Comfort	Uncomfortable	No data	Uncomfortable	Uncomfortable	Uncomfortable	Uncomfortable	No data	Uncomfortable
	Satisfaction	Dissatisfied	No data	Dissatisfied	Dissatisfied	Dissatisfied	Dissatisfied	No data	Satisfied
	Acceptability	Unacceptable	No data	Unacceptable	Unacceptable	Unacceptable	Unacceptable	No data	Unacceptable
IAQ	**Odour**	Odorous	No data	Odorous	Slightly odorous	Slightly odorous	Slightly odorous	No data	Odorless
	Comfort	Very uncomfortable	No data	Uncomfortable	Slightly uncomfortable	Uncomfortable	Slightly uncomfortable	No data	Slightly uncomfortable
	Satisfaction	Dissatisfied	No data	Dissatisfied	Satisfied	Dissatisfied	N/A	No data	Dissatisfied
	Acceptability	Unacceptable	No data	Unacceptable	Acceptable	Unacceptable	N/A	No data	Acceptable
Air movement	**Movement**	No air movement	No data	No air movement	Slight draught	No air movement	No air movement	No data	No air movement
	Comfort	Uncomfortable	No data	Uncomfortable	Slightly uncomfortable	Uncomfortable	Slightly comfortable	No data	Slightly uncomfortable
	Satisfaction	Dissatisfied	No data	Dissatisfied	Satisfied	Dissatisfied	N/A	No data	Dissatisfied
	Acceptability	Unacceptable	No data	Unacceptable	Acceptable	Unacceptable	N/A	No data	Unacceptable
Humidity	**Humidity**	Dry	No data	Dry	Neutral	Slightly dry	Slightly dry	No data	Slightly dry
	Comfort	Slightly uncomfortable	No data	Uncomfortable	Comfortable	Comfortable	Comfortable	No data	Comfortable
	Satisfaction	Satisfied	No data	Dissatisfied	Satisfied	Satisfied	Satisfied	No data	Satisfied
	Acceptability	Acceptable	No data	Unacceptable	Acceptable	Acceptable	Acceptable	No data	Acceptable
Noise	**Comfort**	Slightly uncomfortable	No data	Comfortable	Slightly uncomfortable	Slightly uncomfortable	Slightly comfortable	No data	Comfortable
	Satisfaction	Satisfied	No data	Satisfied	Satisfied	Satisfied	N/A	No data	Satisfied
	Acceptability	Unacceptable	No data	Acceptable	Acceptable	Acceptable	Acceptable	No data	Acceptable

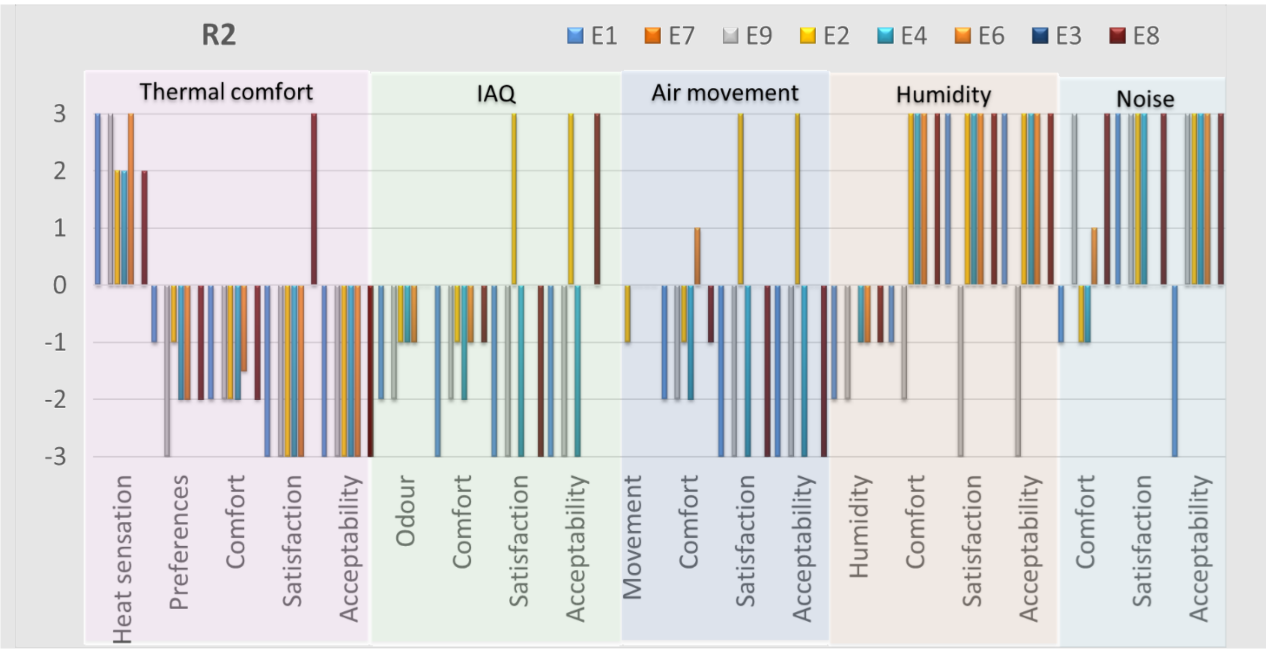


Fig. 28 Room 2 – Summary of questionnaire – numerical (see table 5).

4.3 Room R3 – Air purifier 3

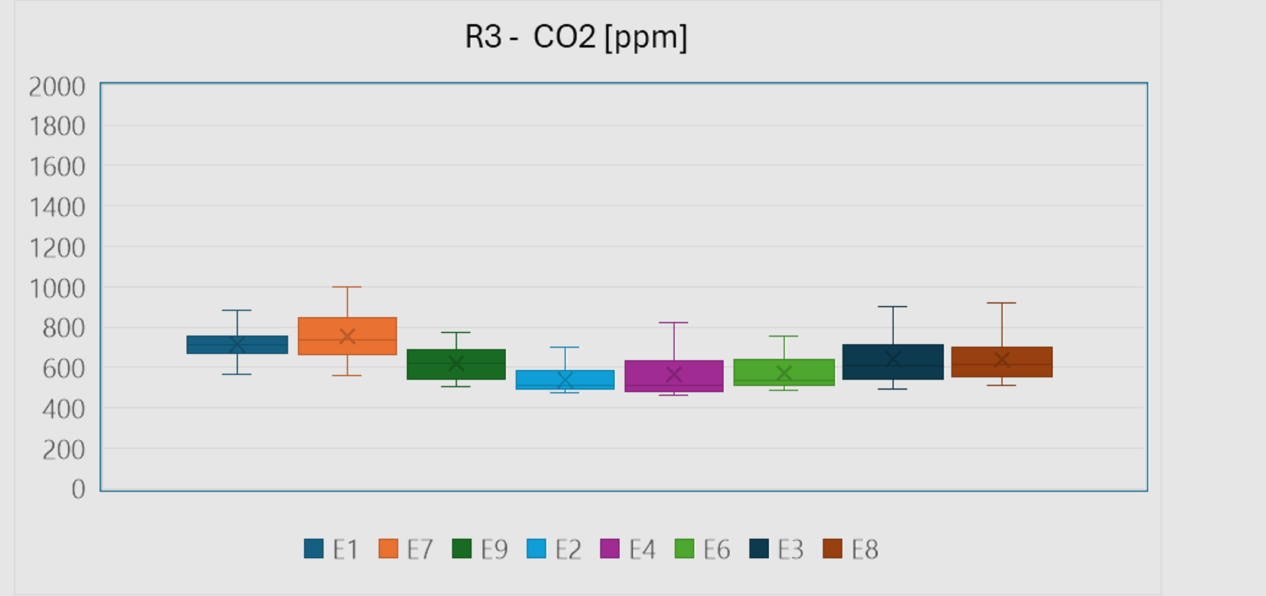


Fig. 29 Room 3 – CO_2 concentration statistic during working hours E1- E8 experiments (see tab 3)

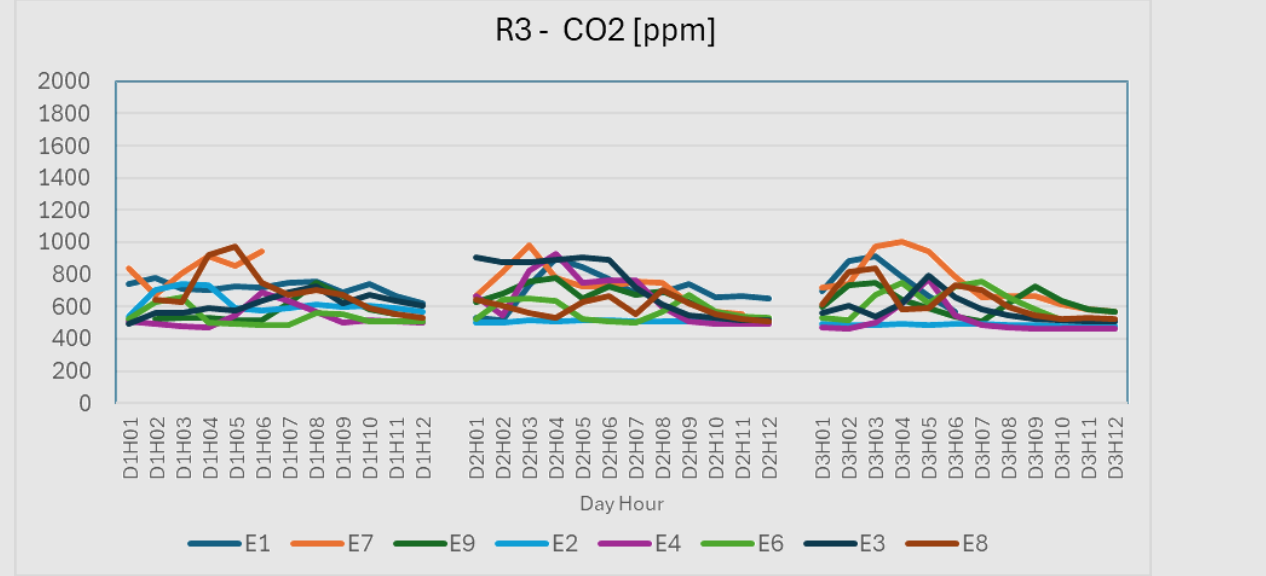


Fig. 30 Room 3 – CO_2 concentration working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 16 Room 3–r CO_2 concentration statistic during working hours

R3 - CO_2 [ppm]	Experiment							
	E1	E7	E9	E2	E4	E6	E3	E8
Min	516,47	556,71	505,48	475,81	462,23	484,81	491,47	511,29
Max	911,82	1001,50	775,56	739,48	927,76	753,15	904,20	977,24
Mean	716,61	755,10	620,44	538,18	566,85	572,59	641,76	638,91
Standard Deviation	92,41	131,66	81,72	69,65	120,88	77,12	129,39	111,92
Quartile 1	666,15	661,12	538,63	492,49	477,72	512,11	540,42	553,97
Quartile 2	713,52	738,62	618,43	510,34	508,20	535,86	606,75	613,12
Quartile 3	759,13	845,41	687,25	584,60	632,79	639,09	713,06	701,13

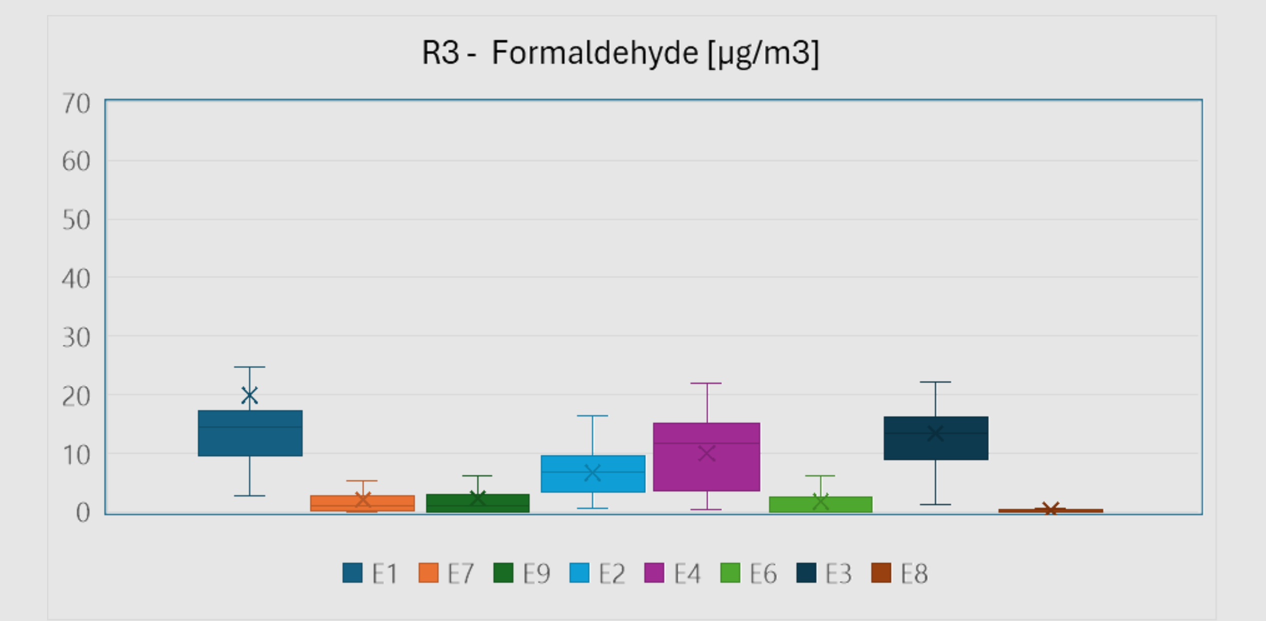


Fig. 31 Room 3– Formaldehyde concentration statistic during working hours E1- E8 experiments (see tab 3)

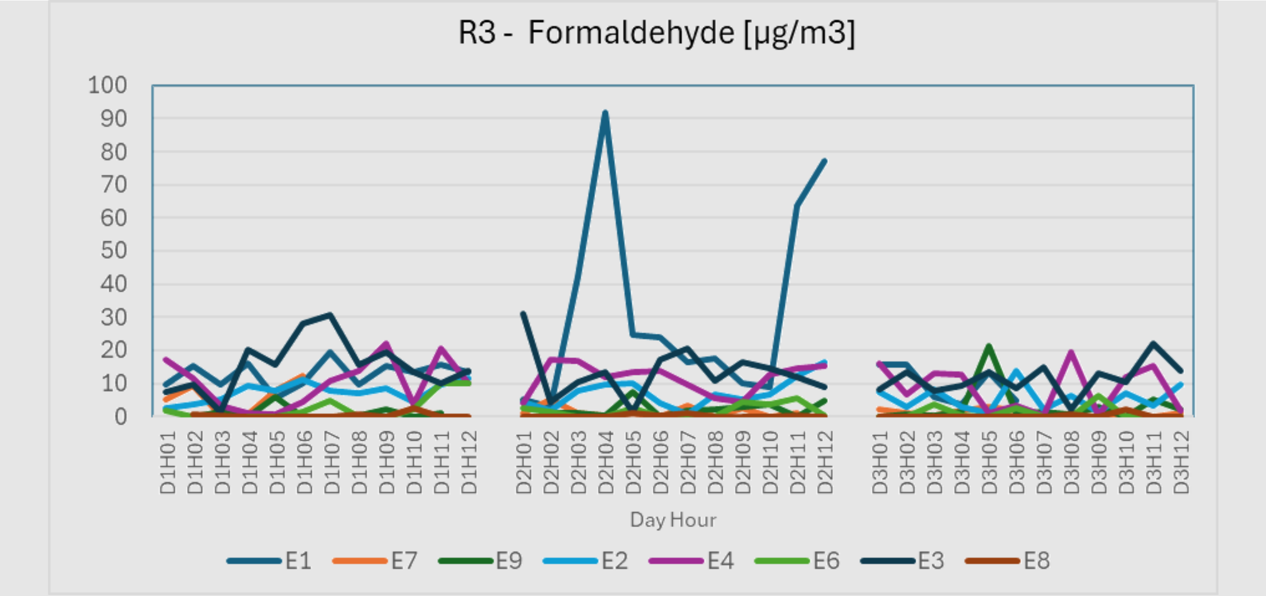


Fig. 32 Room 3 – Formaldehyde concentration working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 17 Room 3– Formaldehyde concentration statistic during working hours

R3 - Formaldehyde [µg/m3]	**Experiment**							
	E1	E7	E9	E2	E4	E6	E3	E8
Min	2,71	0,00	0,00	0,48	0,28	0,00	1,22	0,00
Max	91,92	12,38	21,16	16,29	21,99	10,18	31,08	2,53
Mean	19,87	2,11	2,27	6,66	9,97	1,75	13,40	0,28
Standard Deviation	21,02	3,01	3,82	3,77	6,30	2,70	7,02	0,61
Quartile 1	9,46	0,06	0,00	3,38	3,62	0,00	8,98	0,00
Quartile 2	14,38	1,06	1,02	6,84	11,59	0,00	13,37	0,00
Quartile 3	18,04	2,68	2,90	9,60	15,21	2,50	16,13	0,31

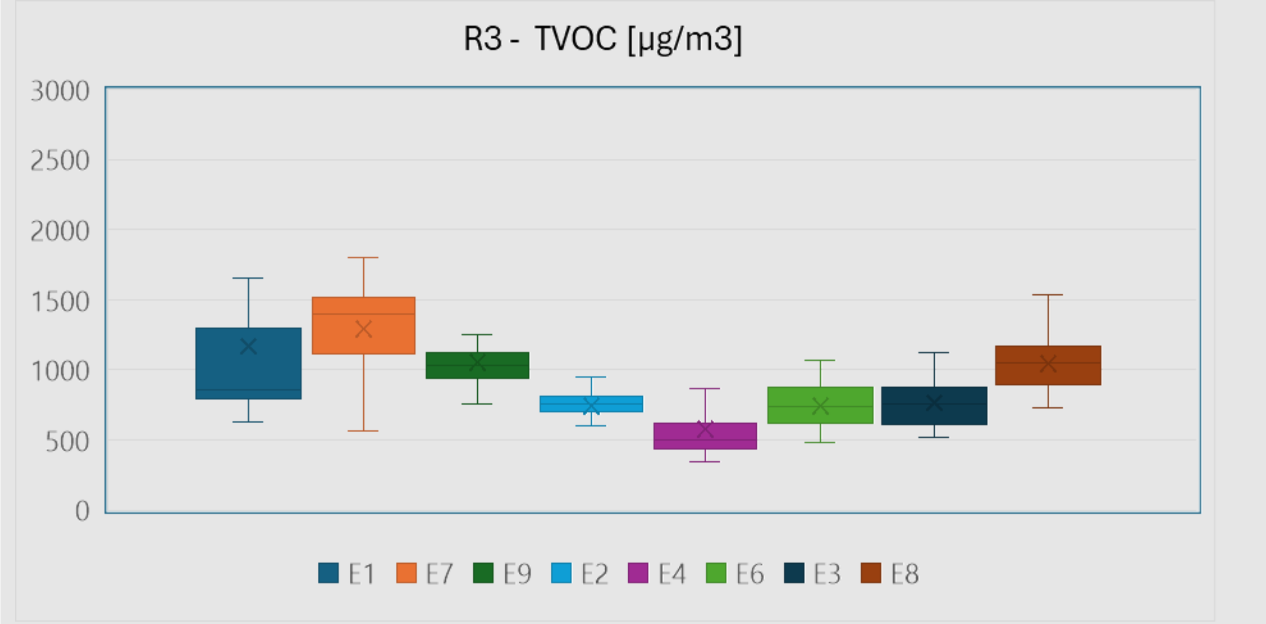


Fig. 33 Room 3– TVOC concentration statistic during working hours E1- E8 experiments (see tab 3)

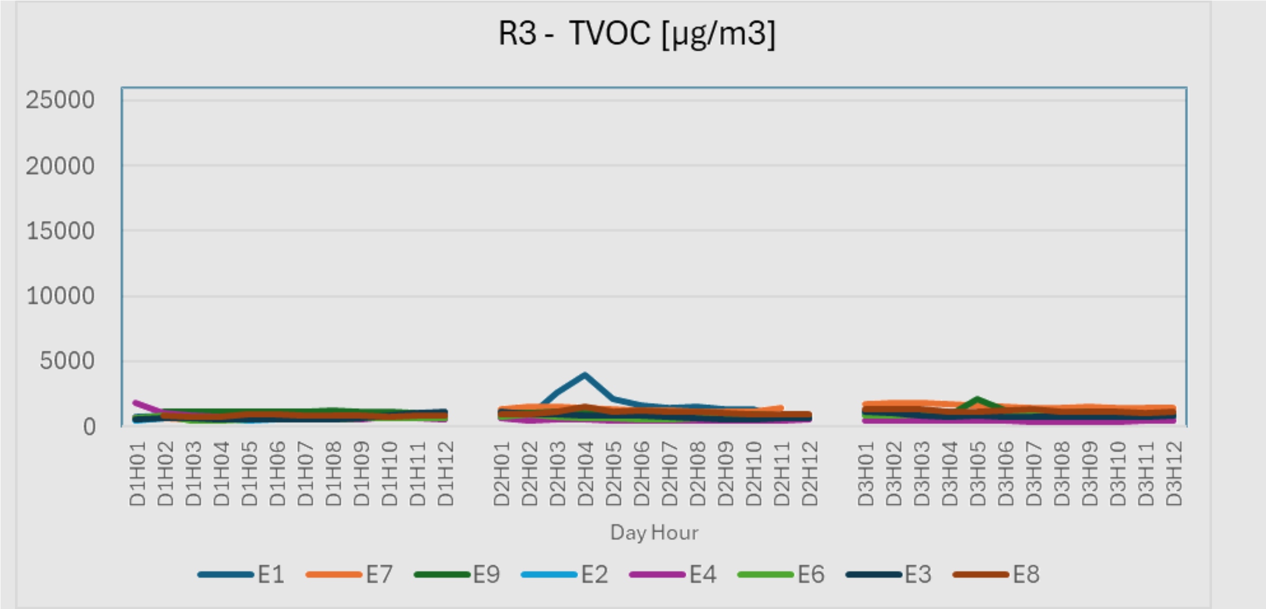


Fig. 34 Room 3 – TVOC concentration working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 18 Room 3– TVOC concentration statistic during working hours

R3 - TVOC [µg/m3]	Experiment							
	E1	E7	E9	E2	E4	E6	E3	E8
Min	626,14	564,80	755,61	443,19	345,08	482,14	514,75	733,44
Max	3946,24	1801,99	2129,47	953,61	1824,18	1066,43	1122,68	1534,51
Mean	1168,34	1291,86	1055,68	741,88	576,51	745,39	768,33	1044,21
Standard Deviation	683,52	360,56	218,84	109,09	255,28	149,20	174,38	188,68
Quartile 1	780,84	1110,84	937,15	706,23	436,82	618,45	610,71	898,59
Quartile 2	855,25	1397,39	1031,61	753,80	499,00	742,02	755,47	1045,97
Quartile 3	1324,99	1519,51	1126,10	812,94	615,25	876,71	872,06	1169,74

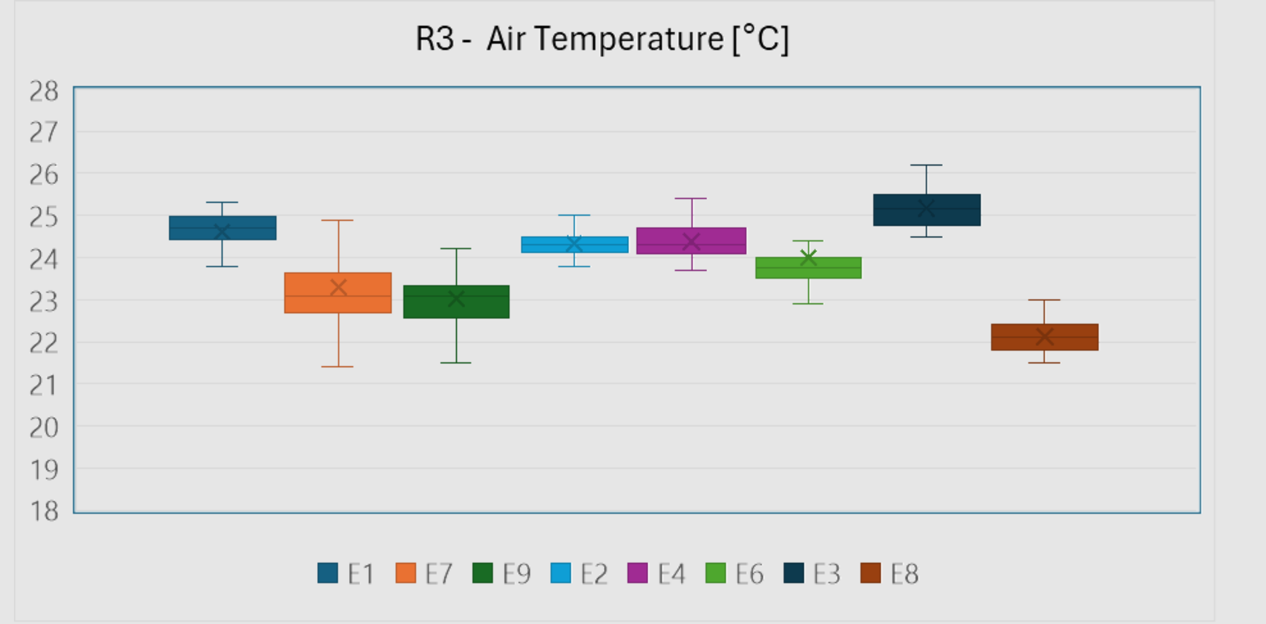


Fig. 35 Room 3– Air temperature statistic during working hours E1- E8 experiments (see tab 3)

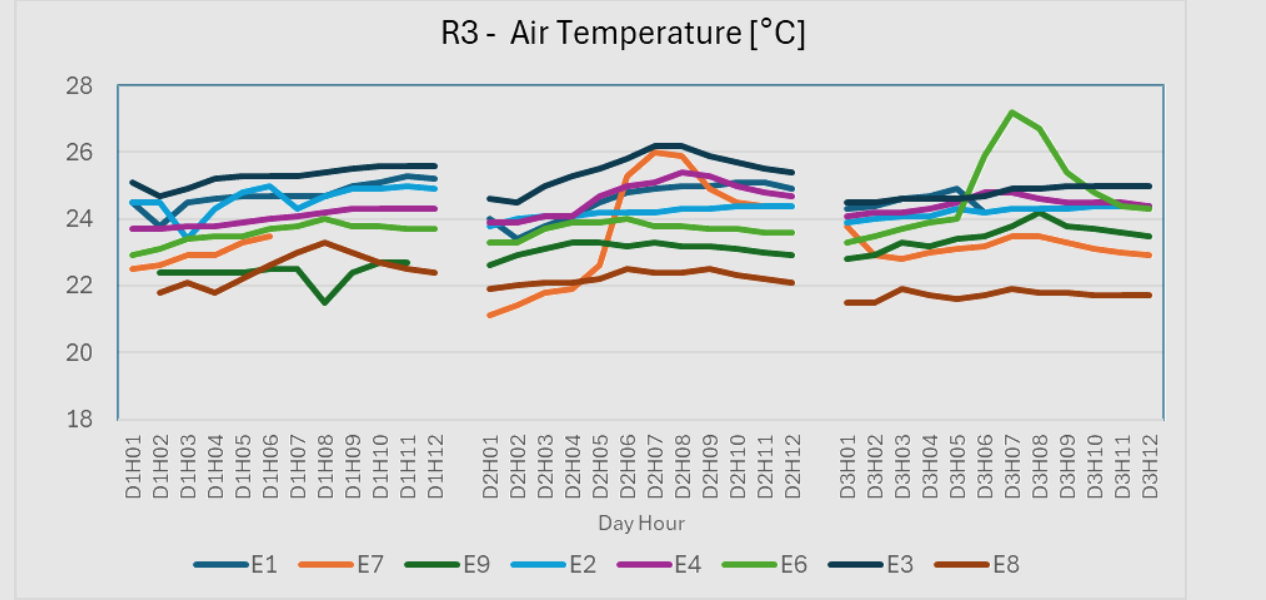


Fig. 36 Room 3 – Air temperature working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 19 Room 3– Air temperature statistic during working hours

R3 - Air Temperature [°C]				Experiment				
	E1	E7	E9	E2	E4	E6	E3	E8
Min	23,40	21,10	21,50	23,40	23,70	22,90	24,50	21,50
Max	25,30	26,00	24,20	25,00	25,40	27,20	26,20	23,30
Mean	24,62	23,30	23,02	24,34	24,38	24,01	25,18	22,13
Standard Deviation	0,45	1,16	0,53	0,34	0,44	0,91	0,47	0,44
Quartile 1	24,38	22,70	22,58	24,13	24,10	23,53	24,75	21,80
Quartile 2	24,70	23,10	23,10	24,30	24,30	23,75	25,15	22,10
Quartile 3	25,00	23,65	23,33	24,48	24,70	24,00	25,50	22,40

Tab. 20 Room 3 – Summary of questionnaire - verbal

R3		E1	E7	E9	E2	E4	E6	E3	E8
Thermal comfort	**Heat sensation**	Hot	Neutral	No data	Hot	No data	Warm	Slightly warm	Neutral
	Preferences	Much cooler	No change	No data	Slightly cooler	No data	Slightly cooler	Cooler	No change
	Comfort	Very uncomfortable	Comfortable	No data	Very uncomfortable	No data	Comfortable	N/A	Comfortable
	Satisfaction	Dissatisfied	Satisfied	No data	Dissatisfied	No data	Satisfied	N/A	Satisfied
	Acceptability	Unacceptable	Acceptable	No data	Unacceptable	No data	Acceptable	N/A	Acceptable
IAQ	**Odour**	Odorous	Odorless	No data	Odorous	No data	Odorless	Slightly odorous	Odorless
	Comfort	Very uncomfortable	Comfortable	No data	Very uncomfortable	No data	Comfortable	N/A	Comfortable
	Satisfaction	Dissatisfied	Satisfied	No data	Dissatisfied	No data	Satisfied	N/A	Satisfied
	Acceptability	Unacceptable	Acceptable	No data	Unacceptable	No data	Acceptable	N/A	Acceptable
Air movement	**Movement**	No air movement	No air movement	No data	No air movement	No data	No air movement	No air movement	Slight draught
	Comfort	Comfortable	Comfortable	No data	Slightly uncomfortable	No data	Comfortable	Slightly comfortable	Comfortable
	Satisfaction	Satisfied	Satisfied	No data	Dissatisfied	No data	Satisfied	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable	No data	Acceptable	No data	Acceptable	Acceptable	Acceptable
Humidity	**Humidity**	Slightly dry	Neutral	No data	Slightly dry	No data	Neutral	Neutral	Neutral
	Comfort	Slightly uncomfortable	Comfortable	No data	Comfortable	No data	Comfortable	Comfortable	Comfortable
	Satisfaction	Satisfied	Satisfied	No data	Satisfied	No data	Satisfied	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable	No data	Acceptable	No data	Acceptable	Acceptable	Acceptable
Noise	**Comfort**	Slightly uncomfortable	Comfortable	No data	Comfortable	No data	Comfortable	Comfortable	Slightly uncomfortable
	Satisfaction	Dissatisfied	Satisfied	No data	Satisfied	No data	Satisfied	Satisfied	Dissatisfied
	Acceptability	Acceptable	Acceptable	No data	Acceptable	No data	Acceptable	Acceptable	Unacceptable

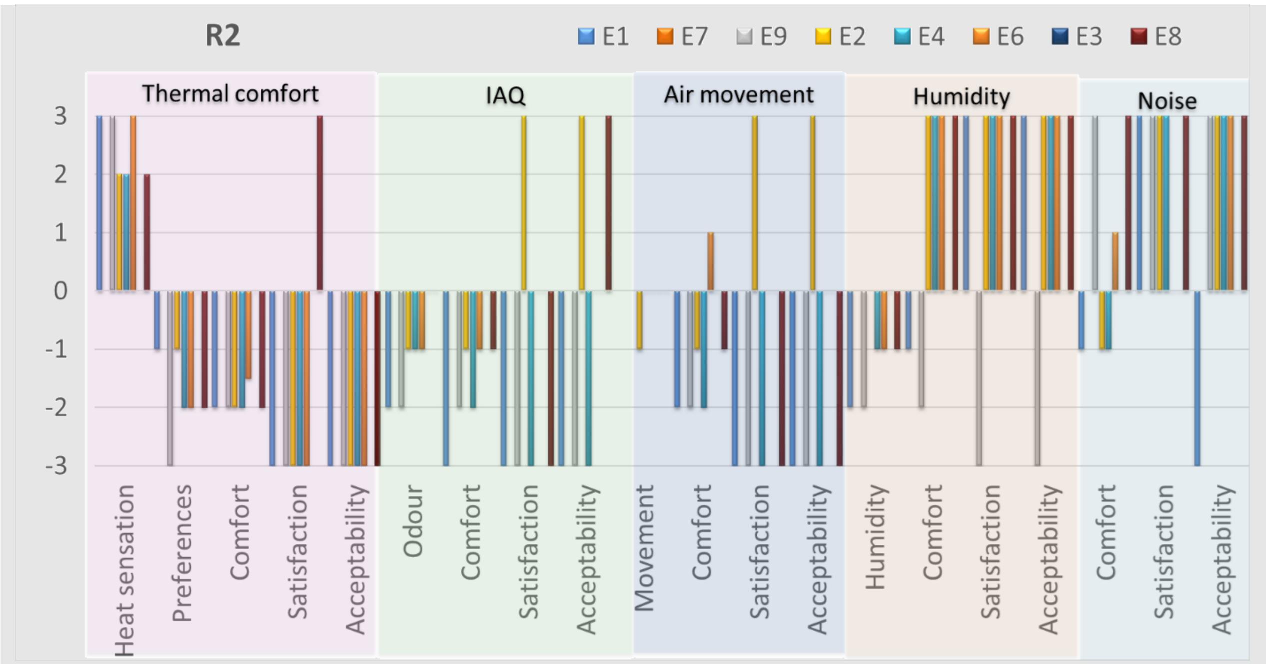


Fig. 37 Room 3 – Summary of questionnaire – numerical (see table 5.

4.4 Room R4 – Reference

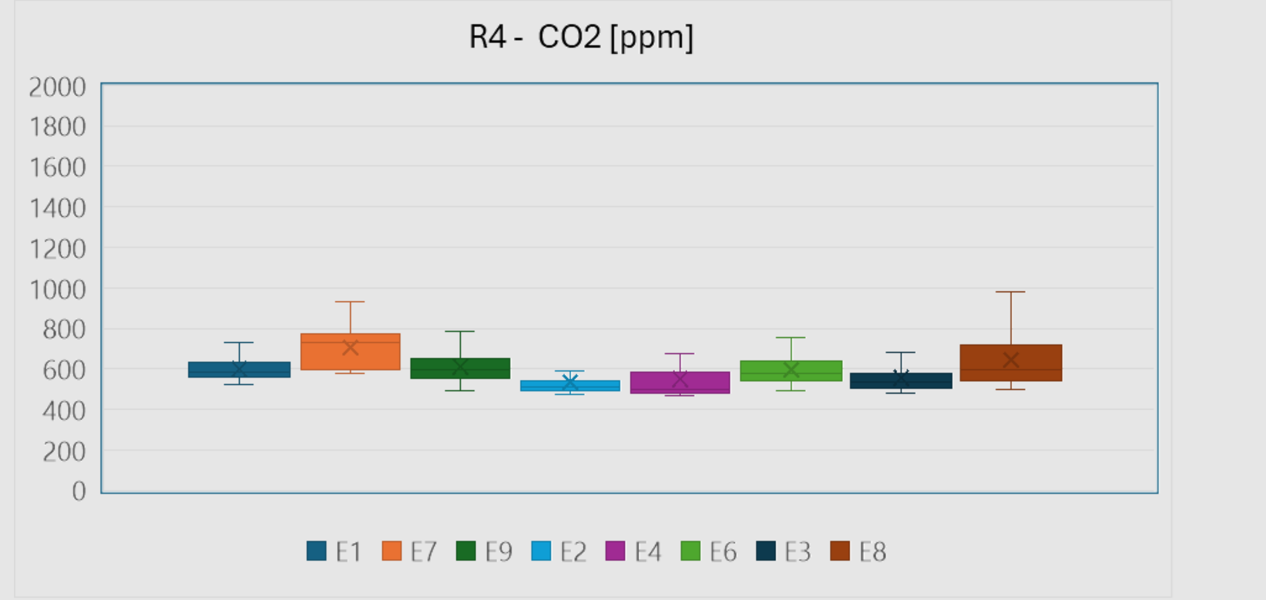


Fig. 38 Room 4 – CO_2 concentration statistic during working hours E1- E8 experiments (see tab 3)

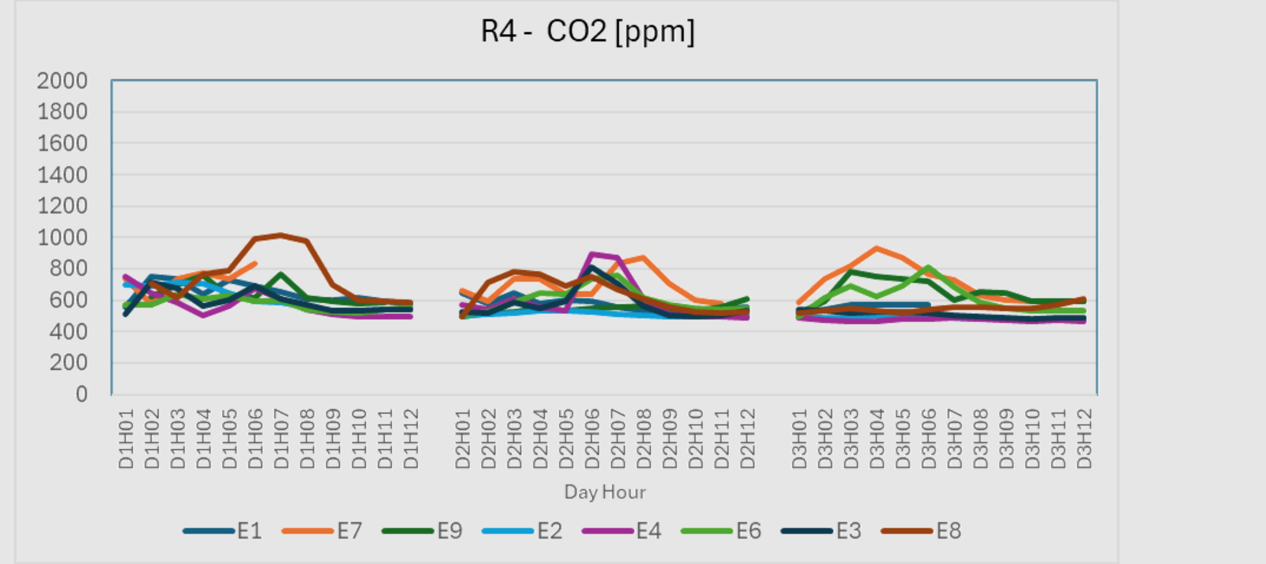


Fig. 39 Room 4 – CO_2 concentration working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 21 Room 4 – CO_2 concentration statistic during working hours

R4 - CO_2 [ppm]	**Experiment**							
	E1	E7	E9	E2	E4	E6	E3	E8
Min	521,76	576,73	494,29	474,88	466,28	493,07	482,96	496,74
Max	749,18	932,19	783,98	714,73	896,23	810,42	812,26	1015,04
Mean	599,26	704,94	611,87	536,53	549,42	595,88	557,85	643,83
Standard Deviation	60,75	102,29	78,10	68,56	104,63	73,16	75,20	137,39
Quartile 1	555,37	597,63	550,67	492,51	482,55	539,80	507,47	538,56
Quartile 2	581,93	731,04	595,14	507,89	499,91	576,95	533,98	595,46
Quartile 3	638,56	770,38	648,75	542,36	581,36	636,68	580,40	716,85

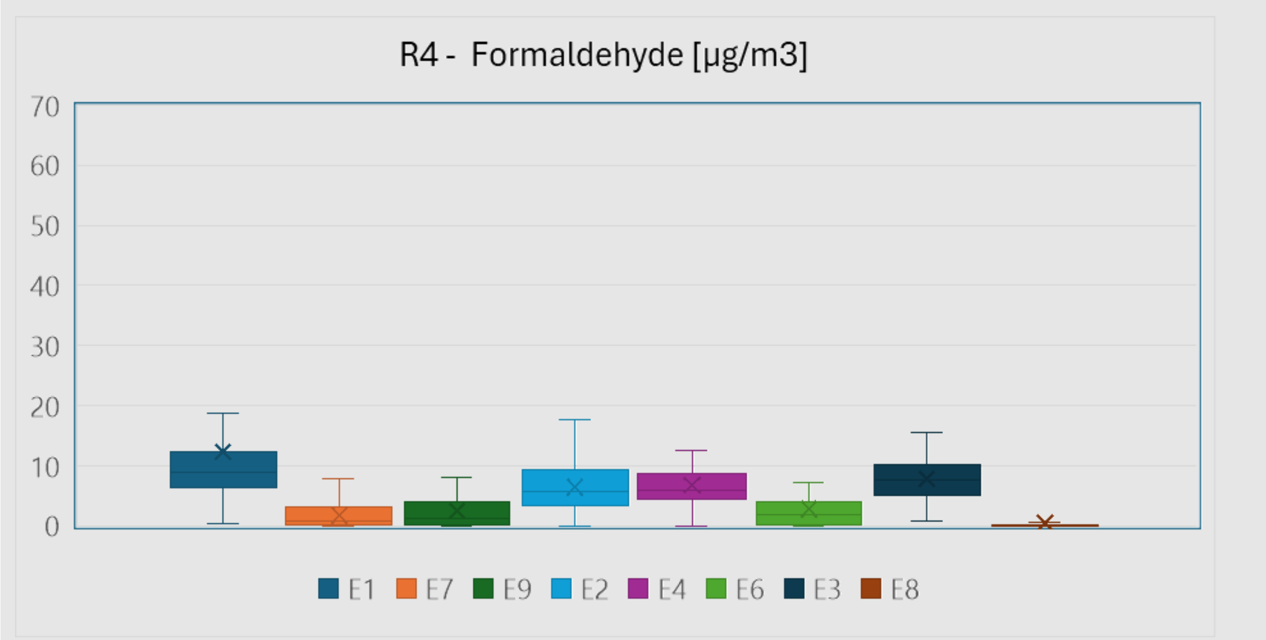


Fig. 40 Room 4 – Formaldehyde concentration statistic during working hours E1- E8 experiments (see tab 3)

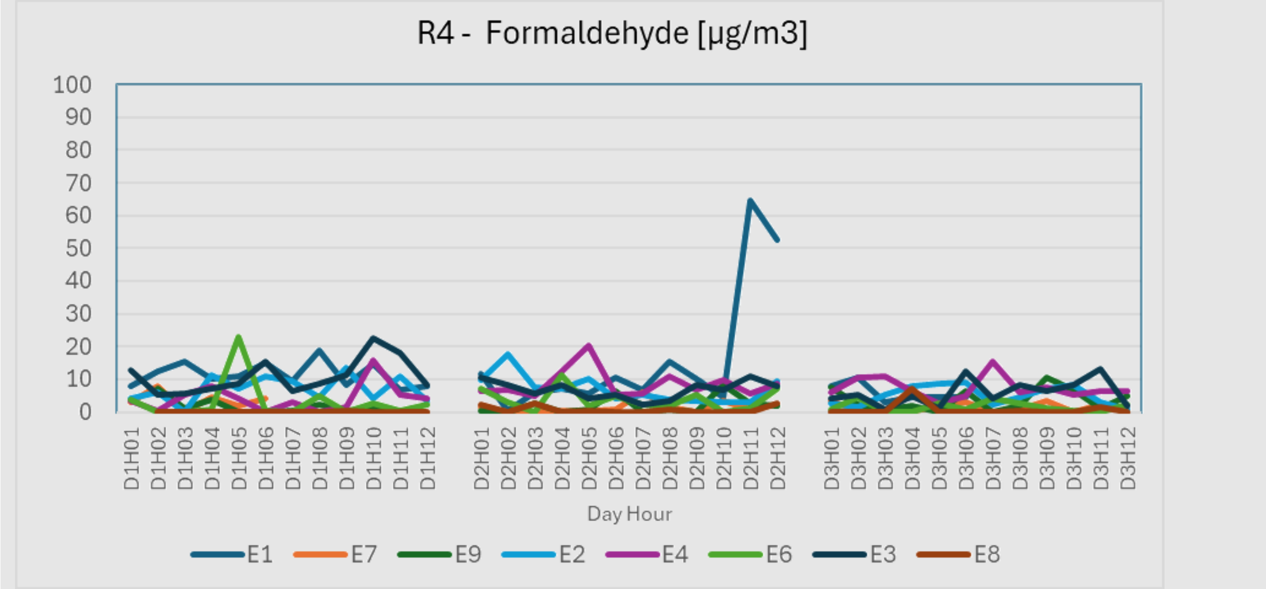


Fig. 41 Room 4 – Formaldehyde concentration working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 22 Room 4 – Formaldehyde concentration statistic during working hours

R4 - Formaldehyde [µg/m3]			**Experiment**					
	E1	E7	E9	E2	E4	E6	E3	E8
Min	0,43	0,00	0,00	0,00	0,00	0,00	0,79	0,00
Max	64,47	7,74	10,64	17,61	20,11	22,98	22,59	7,04
Mean	12,30	1,79	2,48	6,41	6,74	2,87	7,86	0,52
Standard Deviation	13,11	1,98	2,88	3,81	4,28	4,23	4,56	1,33
Quartile 1	6,04	0,19	0,15	3,37	4,38	0,07	4,97	0,00
Quartile 2	8,81	0,82	1,20	5,68	5,98	1,91	7,53	0,00
Quartile 3	13,07	3,23	4,09	9,29	8,64	3,93	10,17	0,25

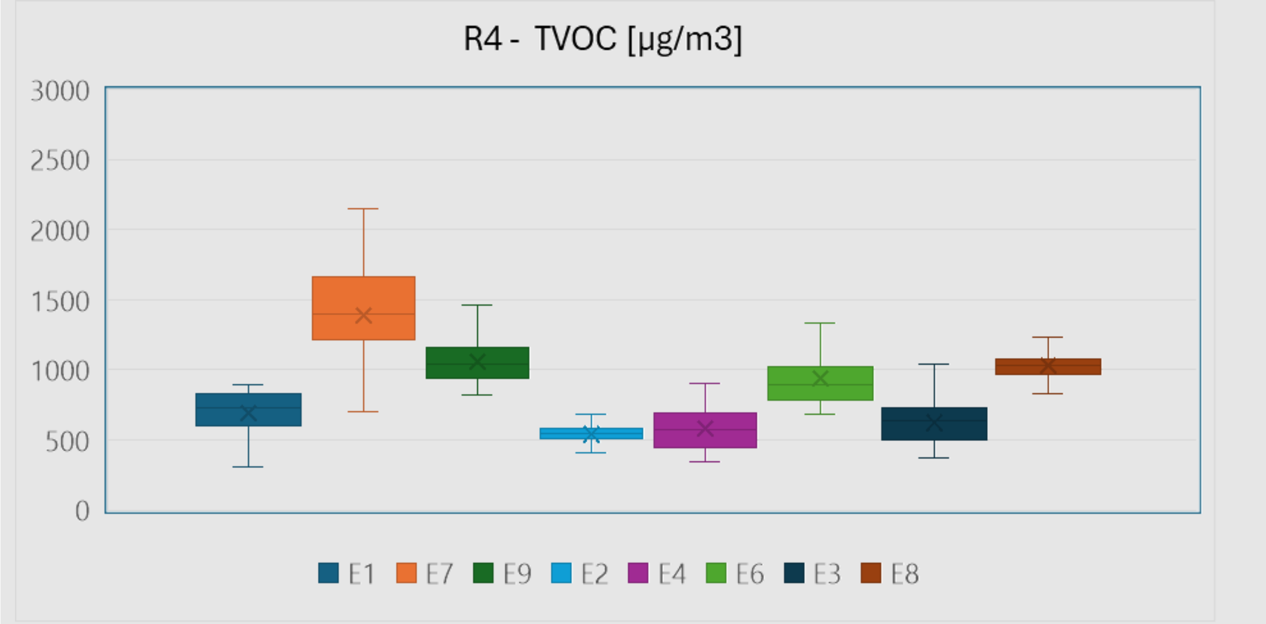


Fig. 42 Room 4 – TVOC concentration statistic during working hours E1- E8 experiments (see tab 3)

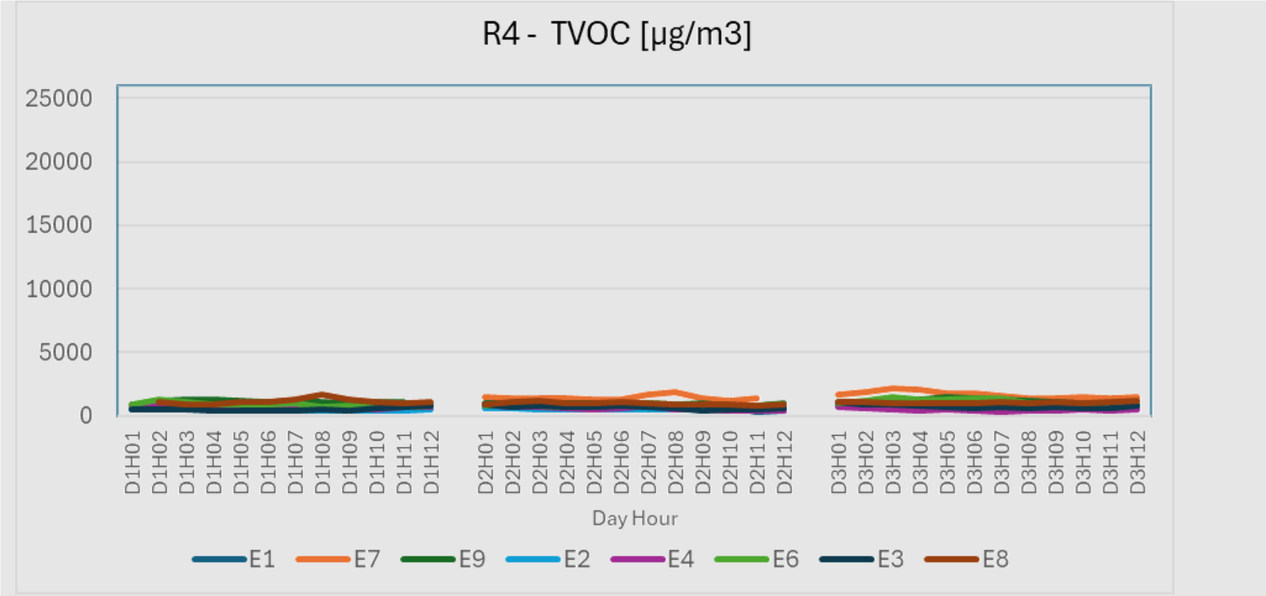


Fig. 43 Room 4 – TVOC concentration working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 23 Room 4 – TVOC concentration statistic during working hours

R4 - TVOC [µg/m3]	**Experiment**							
	E1	E7	E9	E2	E4	E6	E3	E8
Min	309,55	705,39	817,32	356,52	348,33	687,92	371,80	828,19
Max	890,28	2147,99	1459,15	790,25	904,17	1490,92	1043,18	1621,86
Mean	694,63	1389,48	1060,23	543,03	581,40	941,83	625,71	1032,82
Standard Deviation	146,60	380,03	150,32	95,77	148,85	199,94	152,81	142,50
Quartile 1	596,66	1217,27	943,77	511,32	446,26	785,78	503,10	965,23
Quartile 2	728,90	1400,55	1036,26	542,89	575,45	891,04	638,66	1031,83
Quartile 3	832,98	1666,23	1157,45	585,93	691,14	1018,47	732,21	1079,01

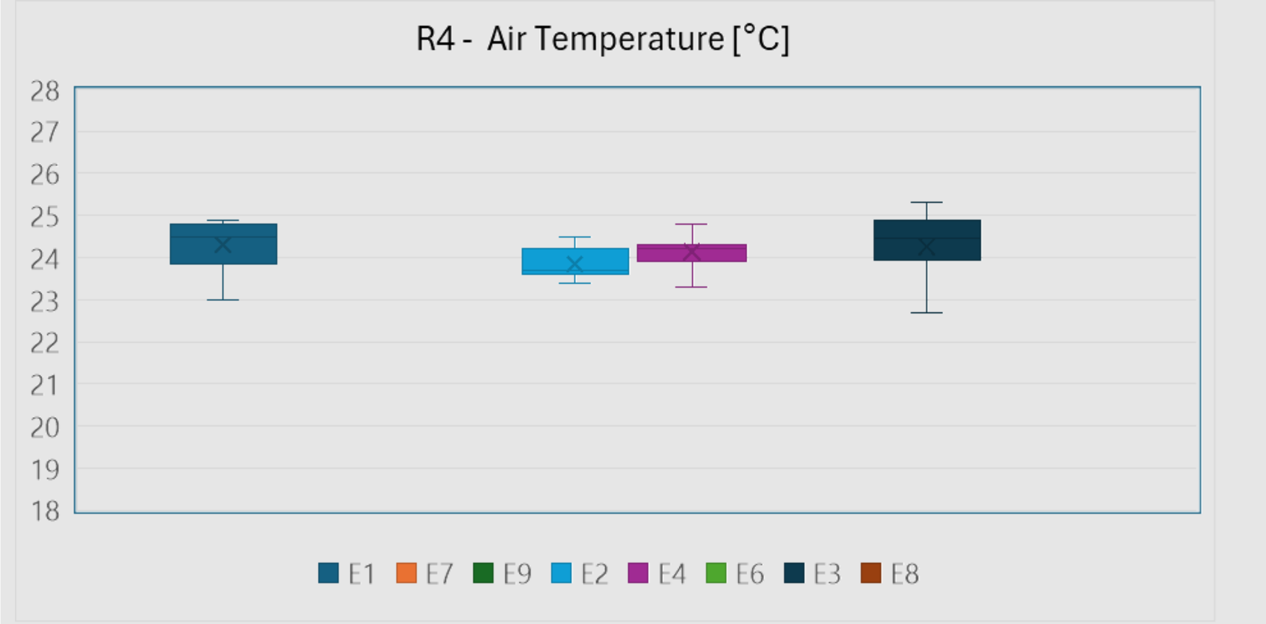


Fig. 44 Room 4 – Air temperature statistic during working hours E1- E8 experiments (see tab 3)

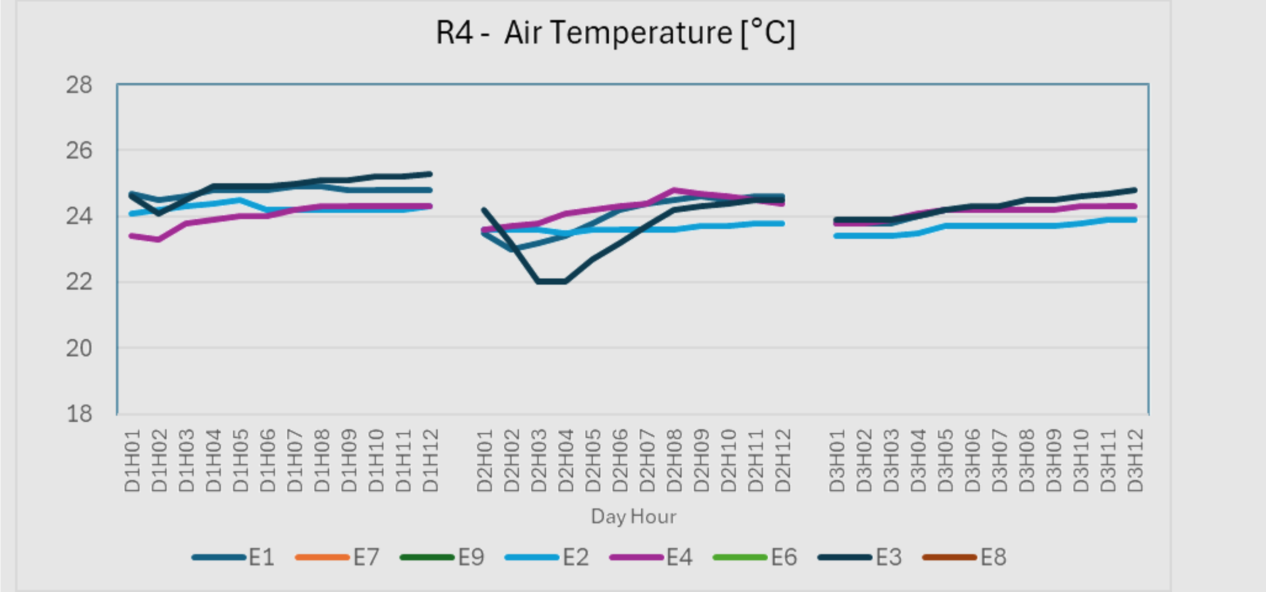


Fig. 45 Room 4 – Air temperature working hours of 3 typical days of each experiment E1- E8 experiments (see tab 3)

Tab. 24 Room 4 – Air temperature statistic during working hours

R4 - Air Temperature [°C]				Experiment				
	E1	E7	E9	E2	E4	E6	E3	E8
Min	23,00	0,00	0,00	23,40	23,30	0,00	22,00	0,00
Max	24,90	0,00	0,00	24,50	24,80	0,00	25,30	0,00
Mean	24,31	0,00	0,00	23,85	24,13	0,00	24,26	0,00
Standard Deviation	0,54	0,00	0,00	0,31	0,33	0,00	0,80	0,00
Quartile 1	23,80	N/A	N/A	23,60	23,90	N/A	23,93	N/A
Quartile 2	24,50	N/A	N/A	23,70	24,20	N/A	24,45	N/A
Quartile 3	24,80	N/A	N/A	24,20	24,30	N/A	24,88	N/A

Tab. 25 Room 4 – Summary of questionnaire - verbal

R4		E1	E7	E9	E2	E4	E6	E3	E8
Thermal comfort	**Heat sensation**	Slightly warm	Slightly warm	No data	Slightly warm	Neutral	No data	Neutral	Slightly warm
	Preferences	Cooler	No change	No data	No change	No change	No data	No change	No change
	Comfort	Slightly uncomfortable	Slightly uncomfortable	No data	Comfortable	Slightly uncomfortable	No data	Comfortable	Comfortable
	Satisfaction	Satisfied	Satisfied	No data	Satisfied	Satisfied	No data	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable	No data	Acceptable	Acceptable	No data	Acceptable	Acceptable
IAQ	**Odour**	Slightly odorous	Odorless	No data	Odorless	Slightly odorous	No data	Slightly odorous	Odorless
	Comfort	Slightly uncomfortable	Comfortable	No data	Comfortable	Uncomfortable	No data	Uncomfortable	Comfortable
	Satisfaction	Satisfied	Satisfied	No data	Satisfied	Dissatisfied	No data	Dissatisfied	Satisfied
	Acceptability	Acceptable	Acceptable	No data	Acceptable	Unacceptable	No data	Unacceptable	Acceptable
Air movement	**Movement**	No air movement	No air movement	No data	Slight draught	No air movement	No data	No air movement	No air movement
	Comfort	Slightly uncomfortable	Slightly uncomfortable	No data	Slightly uncomfortable	Uncomfortable	No data	Slightly uncomfortable	Comfortable
	Satisfaction	Dissatisfied	Satisfied	No data	Satisfied	Dissatisfied	No data	Dissatisfied	Satisfied
	Acceptability	Acceptable	Acceptable	No data	Acceptable	Unacceptable	No data	Unacceptable	Acceptable
Humidity	**Humidity**	Slightly dry	Slightly dry	No data	Neutral	Neutral	No data	Slightly humid	Dry
	Comfort	Slightly uncomfortable	Uncomfortable	No data	Comfortable	Comfortable	No data	Slightly uncomfortable	Uncomfortable
	Satisfaction	Satisfied	Dissatisfied	No data	Satisfied	Satisfied	No data	Satisfied	Dissatisfied
	Acceptability	Acceptable	Unacceptable	No data	Acceptable	Acceptable	No data	Acceptable	Unacceptable
Noise	**Comfort**	Very uncomfortable	Comfortable	No data	Uncomfortable	Comfortable	No data	Comfortable	Comfortable
	Satisfaction	Dissatisfied	Satisfied	No data	Dissatisfied	Satisfied	No data	Satisfied	Satisfied
	Acceptability	Unacceptable	Acceptable	No data	Unacceptable	Acceptable	No data	Acceptable	Acceptable

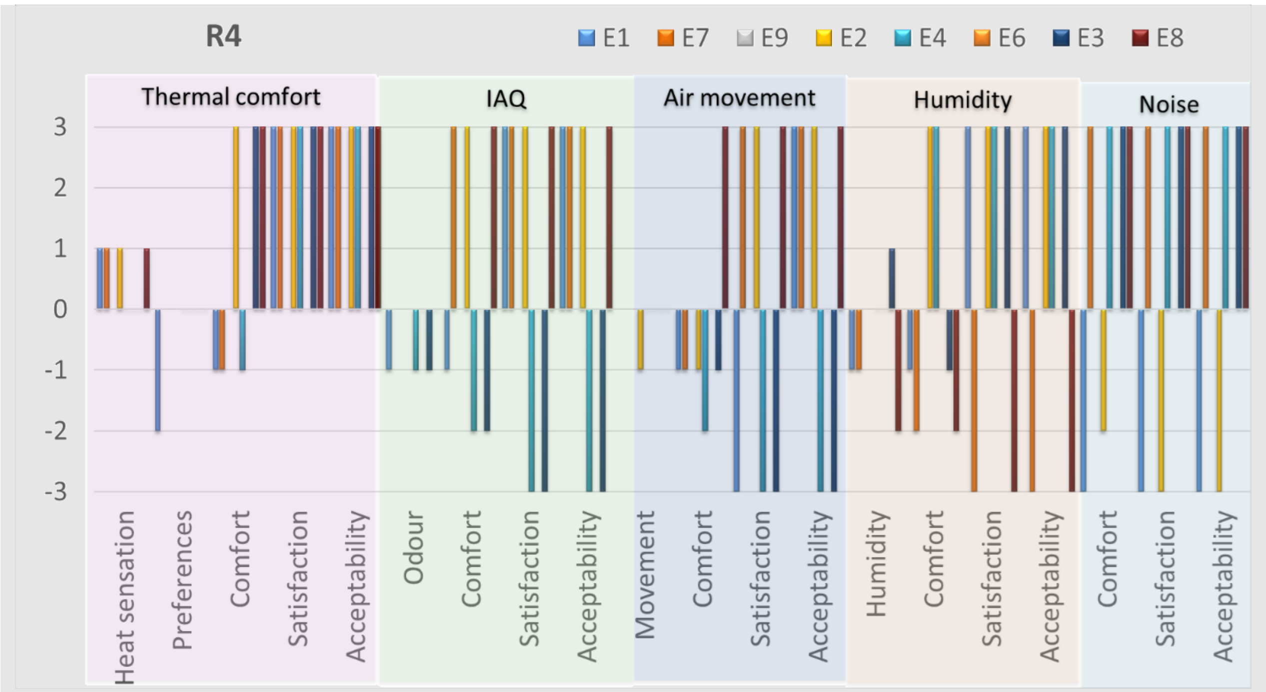


Fig. 46 Room 4 – Summary of questionnaire – numerical (see table 5)

5. Results analysis and discussion

5.1 Impact of Air Purifier on Pollutant Concentration

Method Used: To determine the impact of the air purifier on pollutant concentration, the average decrease in pollutant concentration over a three-day cycle during working hours was calculated from the measured values. The method is based on the hypothesis that if the air purifier has an effect on the given pollutant, the decrease in its concentration will be faster than without the purifier. The difference between successive average hourly concentrations was evaluated. Subsequently, experiments where the air purifier was operational (E1, E7) were compared with experiments where the air purifier was operational without installed filters, the so-called placebo effect (E3, E8). In all compared cases, the ventilation system was set to the first performance level, and users were instructed to minimize door openings and keep windows closed. Experiments E1 and E3 were conducted in the spring, while experiments E7 and E8 were conducted in the winter.
The results of the comparison in absolute values of the average decrease in pollutant concentration are presented in the following tables. Rooms R1 to R3 were equipped with air purifiers, while room R4 was a reference room without an air purifier.

The exact calculation method for the average hourly change in pollutant concentration during the three-day cycle, as described in the provided text, involves the following steps:

1. Measurements of pollutant concentrations (such as formaldehyde and TVOC) were recorded hourly during working hours across the three-day experimental cycle.
2. For each hour, the difference in pollutant concentration from the previous hour was calculated, i.e. the drop in concentration compared to the preceding hourly measurement.
3. These hourly differences were averaged over the entire three-day period to produce an average hourly decrease.
4. This average decrease was then compared between experiments with the air purifier fully operational (E1 and E7) versus placebo experiments where the purifier operated without filters (E3 and E8), all under controlled ventilation and occupant behavior.

This method relies on using sequential hourly concentration values, calculating the difference between each time point, and then averaging these differences to estimate the mean rate of pollutant decrease per hour during working periods. This approach quantifies how quickly pollutant concentrations decline in the indoor environment under different purifier conditions.

Tab. 26 Formaldehyde - average decrease in pollutant concentration during a three-day cycle over the course of working hours.

Formaldehyde [μg/m^3]						
Room	**E1 - with, spring**	**E3 - without, spring**	**E7 with, winter**	**E8 - without, winter**	**E1/E3 spring**	**E7/E8 winter**
R1	-19	-10	-3	-6	188%	60%
R2	-5	-7	-2	-3	82%	75%
R3	-10	-8	-2	-1	123%	232%
R4	-7	-5	-3	-2	133%	172%

Tab. 27 TVOC - average decrease in pollutant concentration during a three-day cycle over the course of working hours.

TVOC [µg/m³]						
Room	**E1 - with, spring**	**E3 - without, spring**	**E7 with, winter**	**E8 - without, winter**	**E1/E3 spring**	**E7/E8 winter**
R1	-299	-137	-80	-193	218%	41%
R2	-1505	-75	-66	-164	2007%	40%
R3	-273	-72	-70	-85	380%	83%
R4	-83	-70	-144	-92	117%	156%

5.1.1 Room R1

In terms of formaldehyde, a greater effect of the air purifier was observed in Room R1 during the spring period, where the decrease in formaldehyde concentration with the purifier on was nearly twice as high as in the experiment without the purifier. However, this effect was not observed in the repeated experiment during the winter period, and conversely, the decrease in concentration was higher with the purifier off. Regarding TVOC concentration, a similar phenomenon was observed in Room R2, meaning that in the spring period, the decrease in concentration was higher with the purifier on than with the purifier off. The repeated test in the winter period did not confirm this phenomenon, and similarly to formaldehyde, the decrease in concentration was smaller with the purifier on than with the purifier off. The air purifier in Room R1 did not show an effect on reducing the concentration of formaldehyde or volatile organic compounds.

5.1.2 Room R2

In terms of formaldehyde, no significant effect of the air purifier was observed in Room R2 during either the spring or winter periods, and the decrease in formaldehyde concentration was approximately the same whether the purifier was on or off. Measurements showed that the decrease in concentration was even slightly higher with the purifier off.

Regarding TVOC concentration in Room R2, the measurement was influenced by the behavior of the subject, who used perfume upon arriving at the office in the morning. This caused extremely high concentrations of volatile organic compounds in the morning hours of experiments E1 and E8, skewing the evaluation of the decrease in this pollutant's concentration. However, from the nature of the concentration decreases, it can be inferred that no significant effect of the air purifier was observed in any of the conducted experiments. The air purifier in Room R2 did not show an effect on reducing the concentration of formaldehyde or volatile organic compounds.

5.1.3 Room R3

In terms of formaldehyde, experiments in Room R3 indicate that the decrease in formaldehyde concentration is faster with the purifier on than with just ventilation. This phenomenon was observed in both experiments, meaning both in the spring and winter periods.

Regarding TVOC concentration in Room R3, a faster decrease in concentration was observed in the spring experiment with the purifier on than with just ventilation. The winter experiment did not confirm this phenomenon, and the rate of decrease was approximately the same in both cases. The experiments suggested an effect of the air purifier in Room R3 on reducing formaldehyde concentration, while no effect was observed for volatile organic compounds.

5.1.4 Room R4

Room R4 was measured as a reference room, in which no air purifier was installed, and the removal of pollutants was achieved solely through ventilation. The measured values and the values evaluated using the aforementioned method demonstrated the average decrease in pollutant concentration during ventilation and confirmed the above conclusions.

5.1.5 Variability in user behavior

Variability in user behavior, such as door opening and perfume use, significantly influenced the results of indoor air quality experiments by introducing variability and noise in pollutant concentration measurements. Opening doors affects the concentrations of formaldehyde (HCHO) and total volatile organic compounds (TVOC) by introducing outside air and disrupting the indoor air stability, causing fluctuations in measured pollutant levels. When doors are opened, the indoor air exchanges with outdoor air, which usually has much lower pollutant concentrations, leading to sudden drops (dilution) in indoor HCHO and TVOC levels. However, this can also bring in outdoor pollutants if outdoor air quality is poor. Specifically:
Opening doors causes transient spikes or drops in pollutant concentrations due to mixing of indoor and outdoor air, which complicates maintaining steady conditions needed for accurate evaluation of air purifier performance. This variability can mask the real effect of the purifier by adding noise to the concentration data, as the change may stem from ventilation events rather than the purifier itself. Thus, experiments tried to minimize door openings to isolate the air purifier's effect. The presence of stable indoor sources of HCHO and VOCs, combined with reduced air exchange when doors are closed, tends to result in a more gradual and controlled decrease of these pollutants, attributed more directly to purifier action or ventilation rate. In summary, door openings introduce uncontrolled ventilation that can both dilute and introduce pollutants, making interpretation of concentration changes more difficult. Minimizing door openings helps better isolate purifier impact in experiments.

Use of perfume or other personal care products indoors can cause spikes in volatile organic compounds (VOCs), as observed in the study where perfume use led to abnormally high TVOC levels during morning hours. Such behaviors create transient peaks that bias average concentration reductions and challenge accurate purifier efficacy evaluation.

Studies show that personalized feedback on indoor pollutant levels can influence user behavior toward reducing pollution sources and better ventilation practices, but initial user activities remain a key factor shaping exposure and measurement outcomes. The behavioral variability underscores the importance of carefully controlling occupant activities and environmental conditions in indoor air quality studies to ensure valid and reproducible results.

In summary, user behavior plays a critical role in indoor pollutant dynamics and influences air purifier effectiveness assessments by adding uncontrollable variability, necessitating controlled experimental design or correction methods in data analysis.

5.2 Impact of air purifier on the effect of an air purifier on the subjective perception of the indoor environment.

To evaluate the effect of the purifier on the subjective perception of the indoor environment, responses to a questionnaire survey were used where responses in each category were compared for related xperiments. Considering the fact that the users did not know the details of the survey or the actual state of turning on or off the purifier, it is possible to deduce certain conclusions with the responses.

5.2.1 Room R1 spring

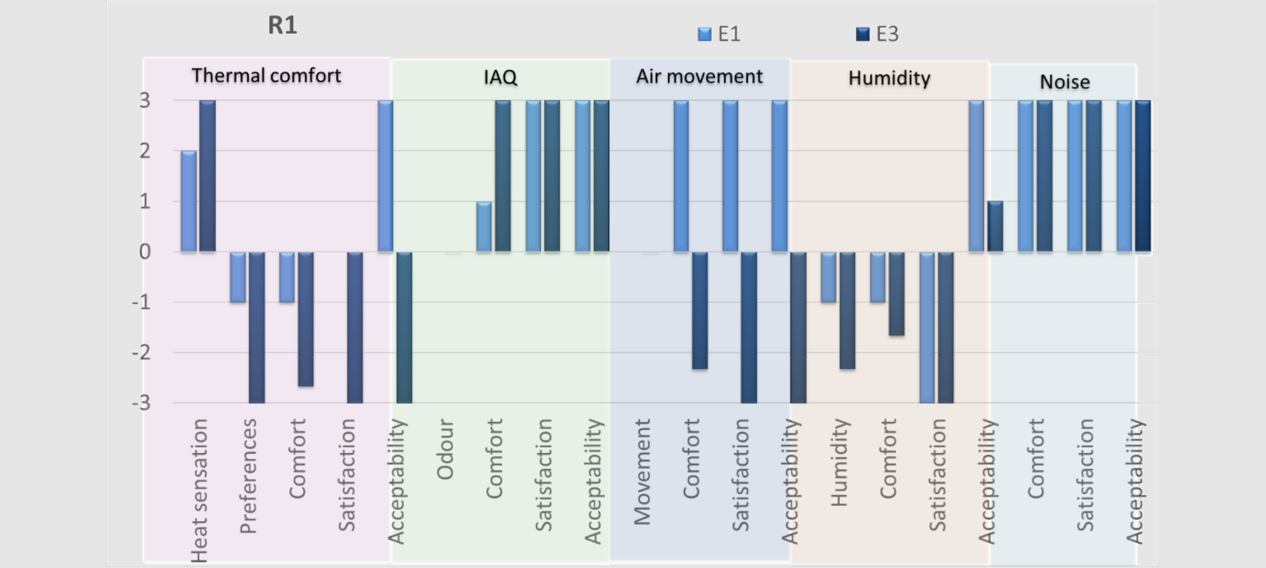


Fig. 47 Room 1 – Summary of questionnaire E1, E3 – spring – numerical (see table 3)

Tab. 28 Room 1 – Summary of questionnaire E1, E3 – spring – verbal

R1 spring		E1 with	E3 without
Thermal comfort	Heat sensation	Warm	Hot
	Preferences	Slightly cooler	Much cooler
	Comfort	Slightly uncomfortable	Very uncomfortable
	Satisfaction	N/A	Dissatisfied
	Acceptability	Acceptable	Unacceptable
IAQ	Odour	Odorless	Odorless
	Comfort	Slightly comfortable	Comfortable
	Satisfaction	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable
Air movement	Movement	No air movement	No air movement
	Comfort	Comfortable	Very uncomfortable
	Satisfaction	Satisfied	Dissatisfied
	Acceptability	Acceptable	Unacceptable
Humidity	Humidity	Slightly dry	Very dry
	Comfort	Slightly uncomfortable	Uncomfortable
	Satisfaction	Dissatisfied	Dissatisfied
	Acceptability	Acceptable	Slightly acceptable

Noise	Comfort	Comfortable	Comfortable
	Satisfaction	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable

In room R1, a comparison of experiments conducted during the spring period shows a positive impact on the subjective perception of the indoor environment in terms of thermal comfort and the perception of air movement.

- **Thermal Comfort:** Respondents experienced a warm to hot sensation overall. Slightly cooler conditions and better comfort were reported without the purifier. Discomfort and dissatisfaction were higher with the purifier on in terms of heat sensation.
- **Indoor Air Quality (IAQ):** Odor was reported as odorless in both cases, with comfort and satisfaction slightly better when the purifier was off.
- **Air Movement:** No air movement was noted in either case, but comfort and acceptability were better without the purifier.
- **Humidity:** Slightly dry conditions were observed with some discomfort and dissatisfaction, worse when the purifier was off.
- **Noise:** Comfortable in both scenarios, with similar acceptability.

5.2.2 Room R1 winter

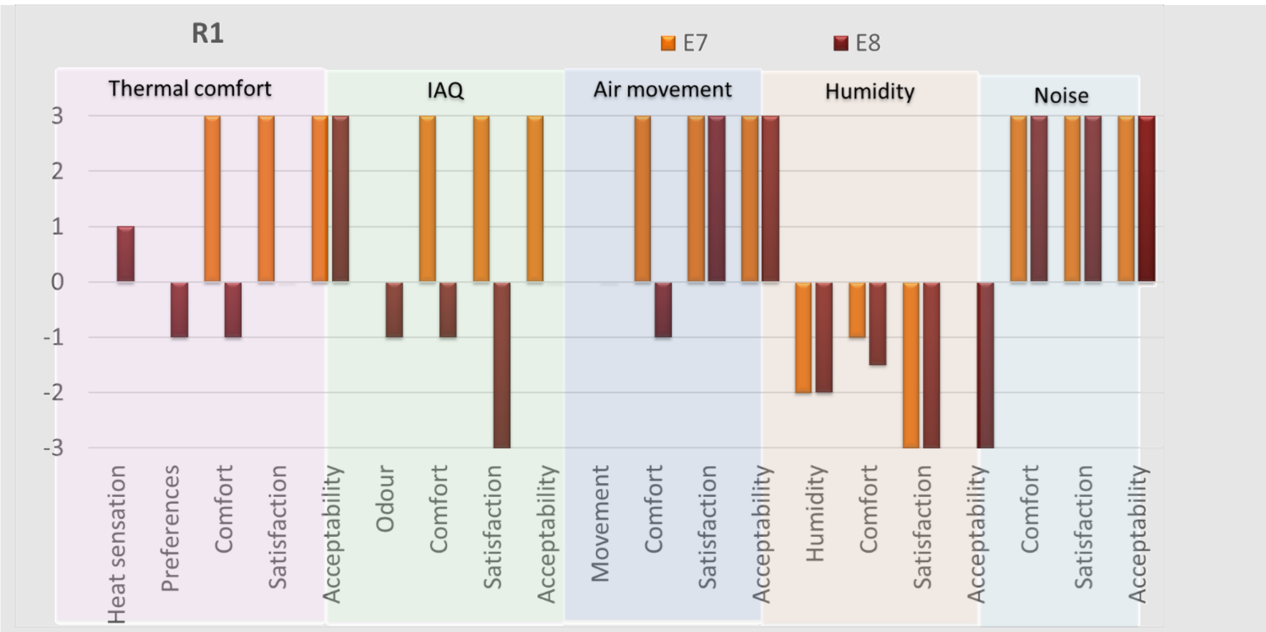


Fig. 48 Room 1 – Summary of questionnaire E1, E3 – winter – numerical (see table 3)

Tab. 29 Room 1 – Summary of questionnaire E1, E3 – winter – verbal

R1 winter		E7 with	E8 without
Thermal comfort	Heat sensation	Neutral	Slightly warm
	Preferences	No change	Slightly cooler
	Comfort	Comfortable	Slightly uncomfortable
	Satisfaction	Satisfied	N/A
	Acceptability	Acceptable	Acceptable

R1 winter		E7 with	E8 without
IAQ	Odour	Odorless	Slightly odorous
	Comfort	Comfortable	Slightly uncomfortable
	Satisfaction	Satisfied	Dissatisfied
	Acceptability	Acceptable	N/A
Air movement	Movement	No air movement	No air movement
	Comfort	Comfortable	Slightly uncomfortable
	Satisfaction	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable
Humidity	Humidity	Dry	Dry
	Comfort	Slightly uncomfortable	Uncomfortable
	Satisfaction	Dissatisfied	Dissatisfied
	Acceptability	N/A	Unacceptable
Noise	Comfort	Comfortable	Comfortable
	Satisfaction	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable

In room R1, when evaluating the experiments carried out in the winter period, a positive effect of the purifier in the part of thermal comfort and air quality can be observed.

- Thermal comfort improved in winter with neutral to slightly warm sensations and higher comfort with the purifier.
- IAQ comfort and satisfaction were better with the purifier, despite an odorless rating in both.
- Air movement remained minimal and comfortable with the purifier on and slightly uncomfortable without.
- Humidity was dry both times, with mild discomfort.
- Noise comfort and satisfaction remained good in both.

Discussion:

In R1, spring time subjective comfort was lower with the purifier on, possibly due to heat or air dryness effects. Winter conditions improved with the purifier, suggesting seasonally varying impacts, likely related to changes in temperature, humidity, and airflow.

5.2.3 Room R2 spring

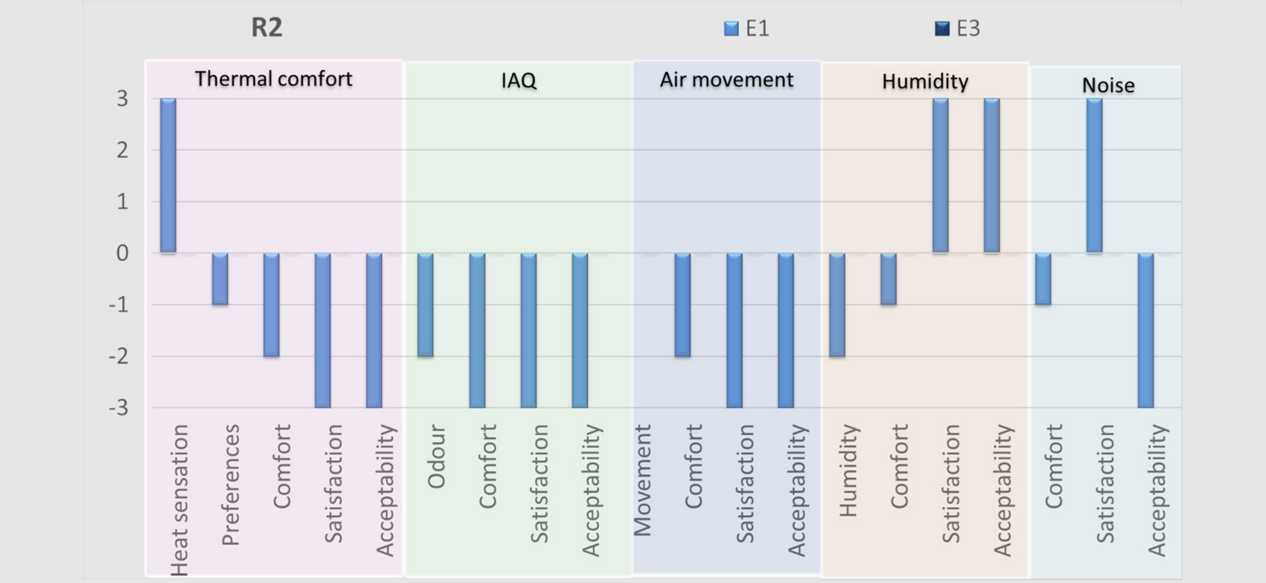


Fig. 49 Room 2 – Summary of questionnaire E1 – spring – numerical (see table 3)

Tab. 30 Room 2 – Summary of questionnaire E1 – spring – verbal

R2 spring		E1
Thermal comfort	Heat sensation	Hot
	Preferences	Slightly cooler
	Comfort	Uncomfortable
	Satisfaction	Dissatisfied
	Acceptability	Unacceptable
IAQ	Odour	Odorous
	Comfort	Very uncomfortable
	Satisfaction	Dissatisfied
	Acceptability	Unacceptable
Air movement	Movement	No air movement
	Comfort	Uncomfortable
	Satisfaction	Dissatisfied
	Acceptability	Unacceptable
Humidity	Humidity	Dry
	Comfort	Slightly uncomfortable
	Satisfaction	Satisfied
	Acceptability	Acceptable
Noise	Comfort	Slightly uncomfortable
	Satisfaction	Satisfied
	Acceptability	Unacceptable

Unfortunately, the respondent in room 2 did not cooperate to the extent required and so we only have responses from 2 experiments instead of 4. The responses show a general dissatisfaction with the environment which was particularly evident in the spring time. The subject complained about the high temperature, however after a deeper analysis of the data the main cause was the inability to open doors and windows at will. This limitation was reflected in the complaints of the other components.

- Thermal comfort was hot, with high discomfort and dissatisfaction, rated unacceptable.
- IAQ was considered odorous and very uncomfortable, with dissatisfaction and non-acceptance.
- No air movement was present, and air movement comfort was similarly negative.
- Humidity was dry with slight discomfort but satisfactory acceptability.
- Noise caused slight discomfort but was somewhat acceptable.

5.2.4 Room R2 winter

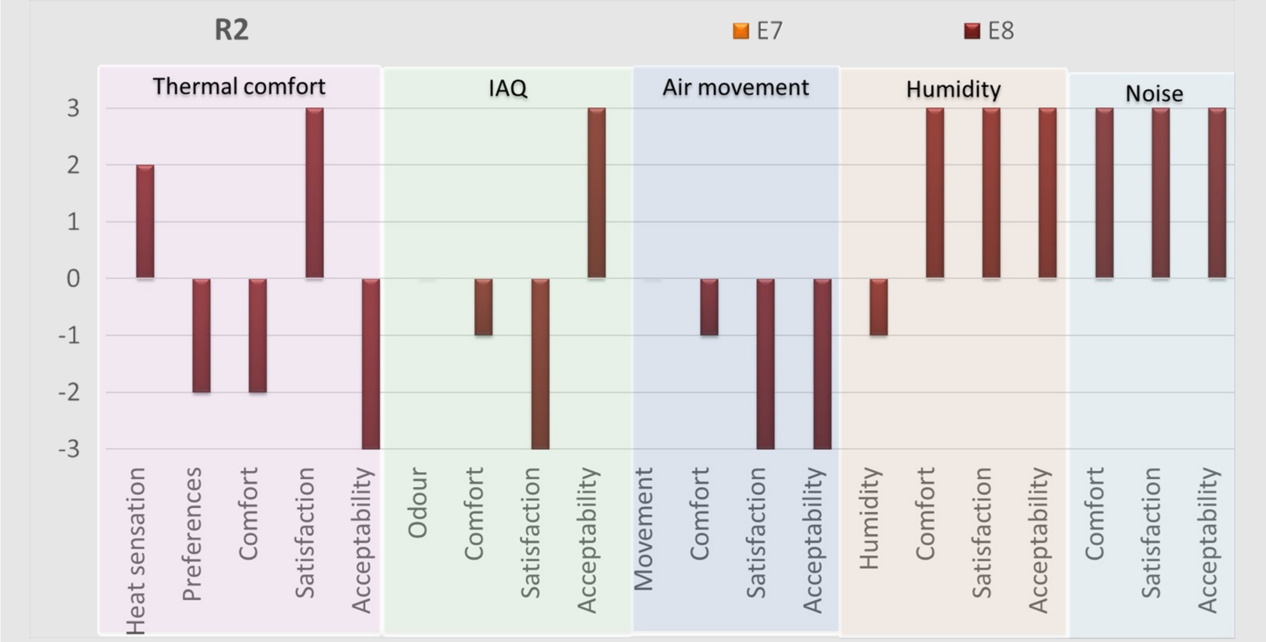


Fig. 50 Room 2 – Summary of questionnaire E8 – winter – numerical (see table 3)

Tab. 31 Room 2 – Summary of questionnaire E8 – winter – verbal

R2 winter		E8
Thermal comfort	**Heat sensation**	Warm
	Preferences	Cooler
	Comfort	Uncomfortable
	Satisfaction	Satisfied
	Acceptability	Unacceptable
IAQ	**Odour**	Odorless
	Comfort	Slightly uncomfortable
	Satisfaction	Dissatisfied
	Acceptability	Acceptable
Air movement	**Movement**	No air movement
	Comfort	Slightly uncomfortable
	Satisfaction	Dissatisfied
	Acceptability	Unacceptable

R2 winter		E8
Humidity	**Humidity**	Slightly dry
	Comfort	Comfortable
	Satisfaction	Satisfied
	Acceptability	Acceptable
Noise	**Comfort**	Comfortable
	Satisfaction	Satisfied
	Acceptability	Acceptable

In winter, due to the lower outdoor temperatures, the complaints about high temperature were less, but still the limitation of the possibility to open the doors led to a negative assessment of the air quality both in terms of the odour microclimate and air movement.

- Warm thermal sensation with uncomfortable conditions but increased satisfaction and acceptability compared to spring.
- Odorless IAQ with slightly uncomfortable comfort but improved satisfaction and acceptance.
- No air movement with mild discomfort and varying acceptability.
- Slightly dry humidity with good comfort and satisfaction.
- Noise was comfortable with good satisfaction and acceptability.

Discussion:

R2 subjectively suffered the most in spring, with poor thermal and air quality comfort linked to odors and dryness, likely associated with external factors like perfume use. Winter conditions were perceived better, possibly due to lover temperature.

5.2.5 Room R3 spring

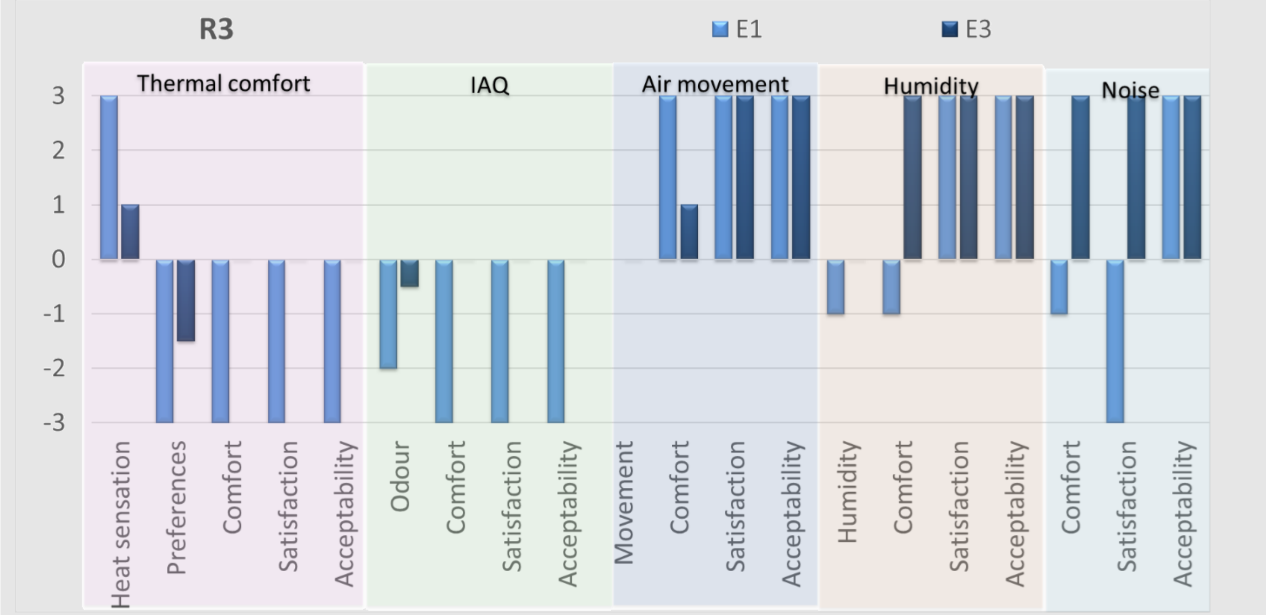


Fig. 51 Room 3 – Summary of questionnaire E1,E3 – spring – numerical (see table 3).

Tab. 32 Room 3 – Summary of questionnaire E1,E3 – spring – verbal

R3 spring		E1	E3
Thermal comfort	Heat sensation	Hot	Slightly warm
	Preferences	Much cooler	Cooler
	Comfort	Very uncomfortable	N/A
	Satisfaction	Dissatisfied	N/A
	Acceptability	Unacceptable	N/A
IAQ	Odour	Odorous	Slightly odorous
	Comfort	Very uncomfortable	N/A
	Satisfaction	Dissatisfied	N/A
	Acceptability	Unacceptable	N/A
Air movement	Movement	No air movement	No air movement
	Comfort	Comfortable	Slightly comfortable
	Satisfaction	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable
Humidity	Humidity	Slightly dry	Neutral
	Comfort	Slightly uncomfortable	Comfortable
	Satisfaction	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable
Noise	Comfort	Slightly uncomfortable	Comfortable
	Satisfaction	Dissatisfied	Satisfied
	Acceptability	Acceptable	Acceptable

Evaluation of the respondent's answers in Room 3 during the spring season indicates dissatisfaction in the areas of thermal comfort and air quality. In both experiments there is a complaint of high temperature, caused secondarily by the inability to open doors and windows at will (similar to the respondent in room 2). Interesting is the complaint about the odour microclimate in the case of experiment E1 where the spread of odour behind the purifiers was evident.

- Thermal conditions were hot with severe discomfort and dissatisfaction with the purifier on; better comfort without.
- IAQ was odorous and very uncomfortable with purifier on, improved slightly without.
- Air movement was absent but air movement comfort remained stable.
- Humidity was slightly dry with slight discomfort.
- Noise caused some discomfort with the purifier on but was comfortable without.

5.2.6 Room R3 winter

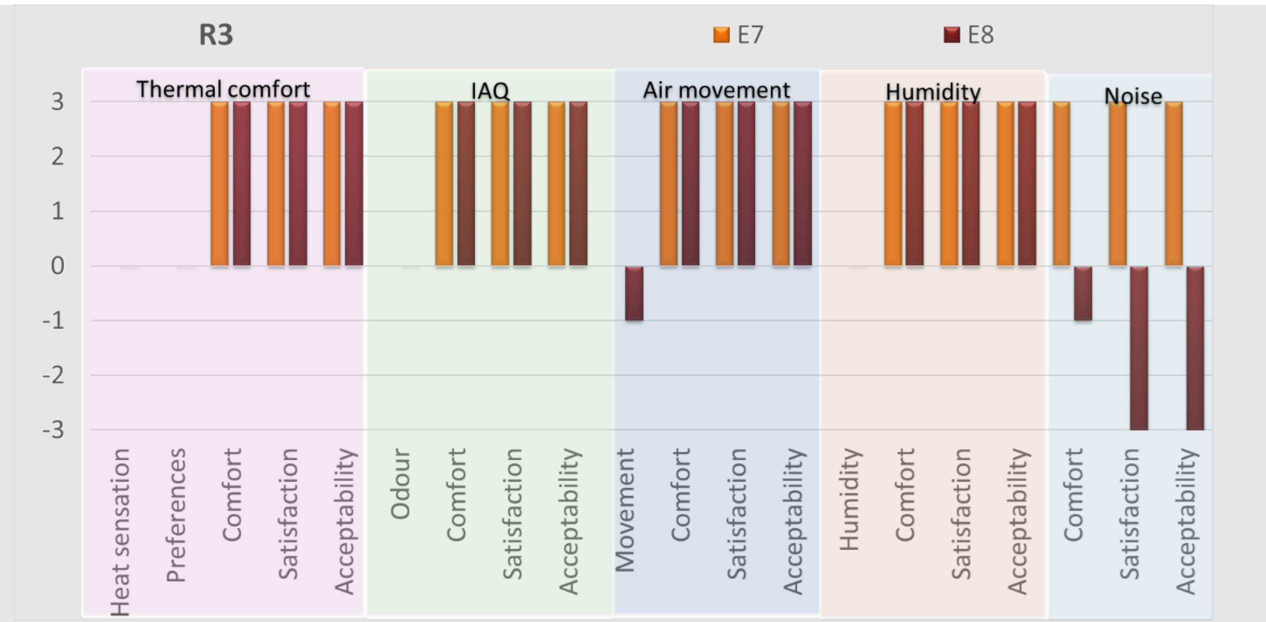


Fig. 52 Room 3– Summary of questionnaire E7, E8 – winter – numerical (see table 3).

Tab. 33 Room 3 – Summary of questionnaire E7, E8 – winter – verbal

R3 winter		E7	E8
Thermal comfort	Heat sensation	Neutral	Neutral
	Preferences	No change	No change
	Comfort	Comfortable	Comfortable
	Satisfaction	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable
IAQ	Odour	Odorless	Odorless
	Comfort	Comfortable	Comfortable
	Satisfaction	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable
Air movement	Movement	No air movement	Slight draught
	Comfort	Comfortable	Comfortable
	Satisfaction	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable
Humidity	Humidity	Neutral	Neutral
	Comfort	Comfortable	Comfortable
	Satisfaction	Satisfied	Satisfied
	Acceptability	Acceptable	Acceptable
Noise	Comfort	Comfortable	Slightly uncomfortable
	Satisfaction	Satisfied	Dissatisfied
	Acceptability	Acceptable	Unacceptable

In the winter season though the responses are more or less identical in both cases except for the acoustic microclimate where in experiment EU the respondent complains about the noise. According to a more detailed analysis of the responses, the noise is from activities outside the room and is not related to the purifier.

- Thermal comfort was neutral and comfortable in both cases.
- IAQ was odorless with good comfort and satisfaction in both.
- Slight air movement appeared in winter without the purifier but comfort remained stable.
- Humidity and noise conditions were neutral and comfortable mostly in both cases, with slightly more noise discomfort without the purifier.

Discussion:
R3 showed significant seasonal differences. In spring, the purifier presence was linked to higher discomfort, especially due to heat and odors, while winter conditions were generally more comfortable and stable regardless of purifier presence. Noise and humidity were stable factors.

6. Conclusions and Recommendations

This comprehensive field study reveals the complex reality of air purifier performance in actual office environments, demonstrating significant variations in effectiveness that differ markedly from laboratory conditions. The investigation of three commercial air purifiers across nine experimental phases provides valuable insights into the practical challenges of implementing air purification technologies in occupied spaces.

The results demonstrate that only one of the three tested air purifiers (Daikin Ururu MCK75JVM-K in Room R3) showed measurable and consistent effectiveness in reducing formaldehyde concentrations during both seasonal periods. This purifier utilized a multi-stage filtration system combining electrostatic filtration, titanium apatite photocatalytic filters, and ionization technology. In contrast, the Ionic-Care Triton X6 (Room R1) and Dyson Purifier Cool Gen1 TP10 (Room R2) failed to demonstrate significant pollutant reduction capabilities under real-world operating conditions.

The limited effectiveness observed can be attributed to several factors inherent to real-world applications. Seasonal variations played a crucial role, with spring experiments showing more pronounced purifier effects compared to winter periods, though results remained inconsistent across different rooms and pollutant types. This seasonal dependency suggests that environmental conditions such as temperature, humidity, and outdoor air quality significantly influence purifier performance in ways not typically captured in standardized testing protocols.

The study reveals that user behaviour represents perhaps the most significant factor affecting air purifier effectiveness in practice. Occupants frequently opened windows and doors for temperature regulation, substantially reducing purifier effectiveness by allowing pollutant infiltration and dilution of treatment effects. This behaviour pattern became more pronounced during spring periods when indoor temperatures reached uncomfortable levels, leading users to prioritize thermal comfort over maintaining the controlled environment necessary for optimal purifier performance.

User compliance decreased systematically over time as occupants became increasingly dissatisfied with operational restrictions imposed by the experimental protocol. This finding highlights a fundamental challenge in real-world air purifier implementation: the tension between optimal technical performance and user acceptance. The study documented specific behavioural impacts, including perfume use that interfered with TVOC measurements and inconsistent adherence to door and window closure protocols.

The non-typical office usage patterns observed in this study, where spaces were occupied intermittently rather than continuously throughout an eight-hour workday, further complicated the assessment of purifier effectiveness. This pattern is representative of many modern flexible office environments but differs significantly from the steady-state conditions assumed in laboratory testing protocols.

Subjective perception assessments through questionnaire surveys revealed mixed results that varied significantly by room, season, and experimental condition. Room R1 showed the most positive subjective improvements, with enhanced thermal comfort and air movement perception when the purifier was active during winter conditions. However, these improvements were not consistent across seasons, with spring conditions showing generally negative responses regardless of purifier operation due to elevated temperatures and restricted window access. The subjective results underscore the complex relationship between objective air quality improvements and occupant satisfaction. Even when measurable pollutant reductions occurred, users did not necessarily perceive improvements in air quality, and in some cases reported decreased satisfaction due to operational restrictions or perceived changes in air movement patterns.

Thermal comfort emerged as the dominant factor influencing overall satisfaction, often overshadowing any air quality benefits provided by the purifiers. This finding suggests that successful air purifier implementation must consider the broader indoor environmental quality context, including thermal and humidity control systems.

Methodological Insights and Limitations

This study's approach of examining air purifier performance under actual operating conditions, rather than controlled laboratory settings, provides valuable insights into the gap between theoretical and practical effectiveness. The methodology intentionally allowed for real-world variability to assess how purifiers perform when subjected to the inconsistencies and behavioral patterns typical of occupied spaces.

The experimental design revealed several methodological challenges that future research must address. The varying experimental durations (5-7 days) and inconsistent ventilation settings between rooms created conditions that, while representative of real-world variation, complicated direct comparisons between purifiers. The limited sample size of questionnaire responses (78 responses from 4 users) restricts the generalizability of subjective findings, though it provides important qualitative insights into user experience patterns.

The study's finding that seasonal conditions significantly affected both objective measurements and subjective perceptions highlights the importance of conducting field evaluations across multiple environmental conditions rather than relying on single-season assessments.

Implications for Building Design and Operation

The results have significant implications for building design and air quality management strategies. The limited effectiveness of air purifiers when windows and doors are frequently opened suggests that these technologies are most suitable for buildings designed with controlled environments, such as those with permanent window sealing or automatic environmental controls.

For existing buildings where occupant behavior cannot be controlled, the study suggests that air purifiers should be viewed as supplementary rather than primary air quality improvement strategies. Integration with building automation systems that can coordinate purifier operation with HVAC systems and occupancy patterns may improve effectiveness while maintaining user comfort.

The findings also indicate that successful air purifier implementation requires comprehensive user education and possibly incentive systems to encourage behaviors that support optimal performance. This might include automated systems that adjust thermal comfort parameters when air purifiers are operating, reducing the likelihood of occupants opening windows for temperature relief.

Recommendations for Future Research

Future research should prioritize investigations in controlled environments where occupants are naturally accustomed to maintaining closed indoor spaces, such as modern office buildings with sealed windows and central climate control. This would provide clearer assessments of air purifier potential without the confounding effects of behavioral variability observed in this study.

Studies should incorporate larger sample sizes with standardized experimental protocols across all tested conditions. Longer observation periods with intermittent breaks could help maintain user cooperation while providing more robust data on long-term effectiveness. Research should also examine the interaction effects between different purifier technologies and specific building characteristics, including ventilation system types, occupancy patterns, and architectural features.

Economic analyses incorporating both direct costs and indirect benefits, including health outcomes and productivity impacts, would provide valuable guidance for implementation decisions. Research into user interface designs and automation systems that minimize the behavioral compliance burden while maintaining effectiveness would address one of the key challenges identified in this study.

Practical Implementation Guidelines

Based on the study findings, several practical guidelines emerge for air purifier implementation in office environments. First, purifiers should be selected based on specific pollutant profiles expected in the target environment, with particular attention to technologies that have demonstrated effectiveness against the pollutants of concern under field conditions rather than laboratory specifications alone.

Installation should prioritize central positioning within rooms with minimal obstructions to air circulation, and coordination with existing HVAC systems to optimize combined effectiveness. Automated control systems that can adjust purifier operation based on occupancy, outdoor air quality, and indoor environmental conditions may improve both effectiveness and user acceptance.

User education programs should emphasize the relationship between environmental control and purifier effectiveness, potentially including real-time feedback on air quality improvements to motivate appropriate behaviors. Maintenance protocols must be established that ensure consistent performance over time, including filter replacement schedules that account for actual operating conditions rather than manufacturer estimates based on idealized conditions.

The study results suggest that air purifiers are most likely to provide meaningful benefits in environments where natural ventilation is limited and where occupants have limited control over window and door operation. In environments where occupants frequently modify the building envelope, alternative or complementary air quality improvement strategies may be more effective.

This research contributes to the growing understanding that effective indoor air quality management requires integrated approaches that consider technology, human behavior, building design, and operational practices as interconnected elements rather than independent variables.

7. Acknowledgment

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