

Indoor living environments: The vitality project in the Marche region (Italy) – integrating sensors and utilities for climatic-environmental monitoring to promote human health

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Abstract *Background and aim:* The integration of sensor-based systems in living environments and microenvironments, both indoor and outdoor, represents a brilliant approach for the continuous and real-time collection of data on climatic-environmental variables (such as air temperature, relative humidity, air velocity, volatile organic compounds, and CO₂). These data are instrumental in supporting decision-making processes to prevent and mitigate negative environmental impacts, particularly in highly vulnerable urban contexts. *Methods:* This paper outlines the research design, objectives, and progress of the Italian PNRR VITALITY Project, SPOKE 6, WP 1.4, titled “Well-being Conditions Between Indoor and Outdoor Spaces”. Specifically, the study focuses on an in-depth analysis of selected indoor climatic-environmental variables that influence human health. Environmental data will be acquired through sensors, processed, and recorded on a digital platform, and integrated into a utility designed for users in three experimental investigation areas (three distinct urban contexts in central Italy, within the Marche Region). *Results:* Operational phases are scheduled to commence by the end of 2025. *Conclusions:* This type of monitoring enables a deeper and context-specific understanding of environmental conditions, providing essential information for the analysis of risk factors and the safeguarding and promotion of well-being and health (www.actabiomedica.it).

Key words: environmental monitoring, healthy environments, indoor environments, health, well-being, sensors

Introduction

Several pieces of evidence have shown that individuals, particularly in high-income countries, spend a significant percentage of their lives in indoor environments, a condition that can reach up to 90% of their daily time (1–9). This trend, known as the “Indoor Generation”, has been further exacerbated by the SARS-CoV-2 pandemic (10,11), which radically altered lifestyle and daily habits by limiting activities such as work, study, sports and entertainment to confined, indoor spaces (12–15). This phenomenon has

been worsen by changing lifestyles and climatic anomalies associated with climate change, contributing to an increasingly indoor and sedentary (7) way of life (6). In recent years, awareness regarding indoor spaces and their need to be healthy and safe has become a widely discussed scientific topic, especially after the pandemic. Additionally, several pieces of evidence are emerging that link indoor microclimate characteristics with both short- and long-term effects on human health (16).

In modern societies, a comfortable thermal environment is provided by air conditioners and heating systems, which are effective in promoting a healthier

environment by reducing stress on human thermoregulatory systems, leading to a significant decrease in mortality due to extreme temperatures (17). However, the poor management of these indoor systems (Heating, Ventilation and Air Conditioning, HVAC) results not only in a significant consumption of unnecessary energy but also in complaints and health issues among occupants (16,18).

The term “indoor environments” or “confined spaces” refers to internal areas delineated by physical structures that separate the interior from the exterior, characterised by variable control over climate conditions, lighting, and ventilation, and designed to accommodate human activities. Their quality directly impacts the health, comfort, and productivity of the occupants, making it necessary to categorise them into specific groups based primarily on their intended use.

In defining a classification of indoor or confined spaces, it is possible to group the main categories based on their function and the structural characteristics that define them. Living environments can be defined as spaces designed to accommodate daily residence and rest activities (19), according to a functional and residential interpretation, such as homes, hostels, dormitories, shelters, etc., or transient places linked to the same rest function (campers, caravans, tents, cabins on ships or trains, etc.), where safety, structural stability, comfort, and climatic conditions play a central role. As living environments, public and private buildings, on the other hand, are distinguished by their accessibility to a wide range of users, addressing administrative, educational, or community needs; representative examples include hospitals, schools, barracks, banks, town halls, airports, etc.

An additional category is represented by structures intended for social purposes, *i.e.*, places designed to facilitate recreational, cultural, commercial, sports or spiritual activities. This includes gyms, sports facilities, cinemas, churches, museums, playgrounds, bars, theatres, restaurants, shops, etc. In contrast, craft and industrial work environments are defined as areas dedicated to production or professional activities, ranging from offices to warehouses, industrial plants, and laboratories, where safety and functionality are prioritised. In addition, public and private transportation systems constitute mobile or temporary environments intended for movement, such as cars, trains,

subways, aeroplanes, and ships, distinguished by their dynamic and transient nature. Finally, technical or specialised environments are characterised by specific requirements for isolation or security. Notable examples include refrigerated warehouses, clean rooms, underground tunnels, and military infrastructures, which serve operational needs (6).

Well-being, comfort, and health risks associated with living environments affect the entire population and are not limited to any category of individuals (6). The most vulnerable groups, such as children, the elderly, and people with chronic conditions, are especially exposed, as they spend considerable time in confined spaces, often of poor quality, particularly in lower-income segments. Health risks should not be assessed solely in professional and occupational terms; on the contrary, the shared interest in well-being places the safety and comfort of living spaces within the framework of public health, making it a crucial element of public health policy. This approach has significant social, economic, and environmental implications.

Beyond the specific abilities of individuals to adapt to the environment, it has been discovered and demonstrated that numerous physico-chemical parameters are correlated with the psycho-physical health of occupants in both indoor and outdoor living spaces. These include air and radiant temperature, relative humidity, air velocity, noise, light intensity, and air quality, defined in terms of the presence or absence of particulate matter (PM), volatile organic compounds (VOCs), and various gases. Additionally, parameters related to lifestyle, such as clothing and the level of physical activity within the environment, also play a role.

Considering the above, despite specific existing regulations and the established knowledge of such associations, the practice of applying sensors for monitoring cognition and actively managing microclimatic and pollution parameters in indoor environments and microenvironments is still not sufficiently widespread, accessible, or encouraged.

In a confined environment, it is essential that users are informed about the presence of potential pollutants and can intervene easily, activating appropriate tools through simple gestures or devices specifically designed for this purpose.

In this context, the VITALITY project, an Ecosystem of Innovation, Digitisation, and Sustainability for the Diffused Economy in Central Italy, within the framework of the National Recovery and Resilience Plan (PNRR) (<https://www.italiadomani.gov.it/it/home.html>), has been implemented (www.fondazionevitality.it). Its primary objective is the transition towards sustainable urban models, with a particular emphasis on well-being, health protection, and the safety of both indoor and outdoor spaces.

Methods

The PNRR VITALITY research initiative involves collaboration among Universities, Research Institutions, and private entities, primarily from the Italian Regions of Abruzzo, Marche, and Umbria (Figure 1).

The whole Project is organised under a Hub & Spoke governance structure, where each Spoke

conducts research on a specific thematic area (<https://fondazionevitality.it/ecosistema/>). Specifically, Spoke 6, Work Package (WP) 1, led by the University of Camerino, aims at an integrated evaluation of urban spaces, where the interpretative and design framework is centred on the relationships between indoor and outdoor environments (<https://fondazionevitality.it/spoke/>).

Within the specific context of WP 1, “*Indoor and Outdoors at the Center of the Digital and Green Transition of Living Environments*”, WP 1.4 focuses on “*Well-being Conditions Between Indoor and Outdoor Spaces*”. The main objective is the design of healthy environments through the processing and analysis of urban, environmental, and architectural parameters that describe the relationship between inhabitants’ health and comfort in living environments through:

- a. The definition of parametric algorithms capable of linking health and well-being conditions

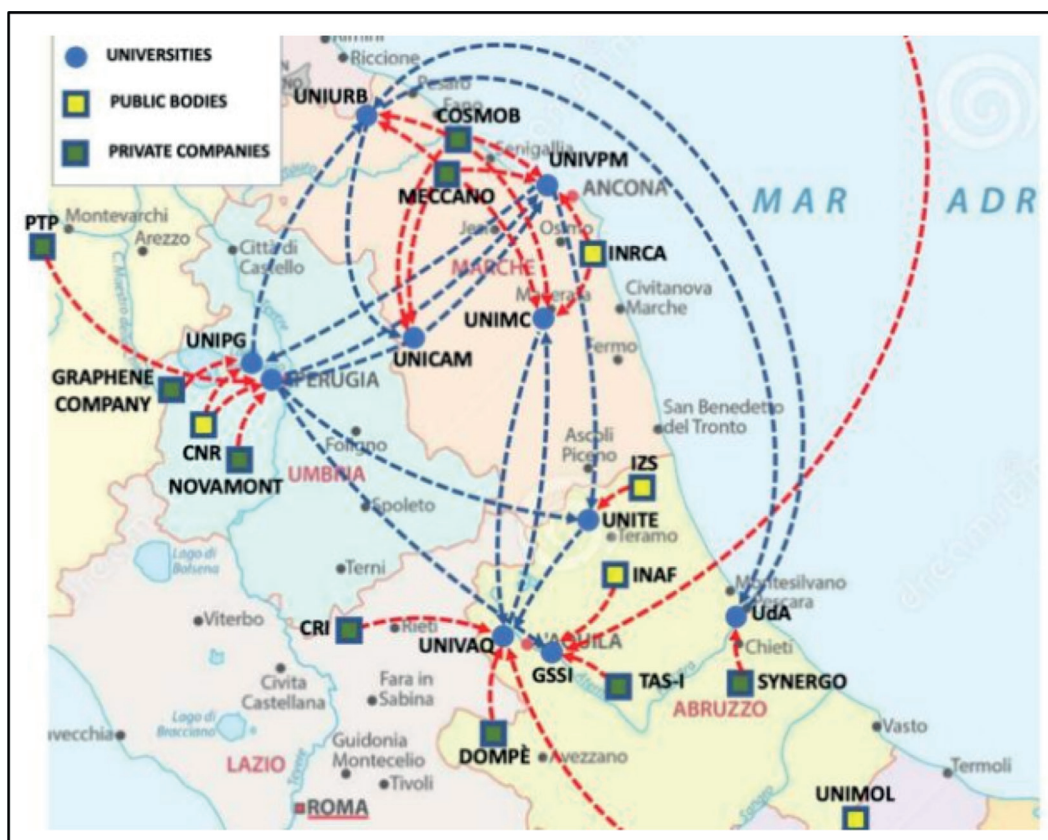


Figure 1. Territorial Distribution of Spokes in the VITALITY Project (www.fondazionevitality.it/ecosistema).

to the environmental characteristics of indoor and outdoor spaces;

- b. The development and implementation of utilities (apps for electronic devices) aimed at raising awareness and promoting the use of spaces that integrate environmental monitoring for health and well-being.

Through this methodology, WP 1.4 not only addresses the challenge of transitioning toward a more integrated model of urban sustainability but also responds to the need for a holistic approach to well-being. In this framework, technology and digitalisation play a crucial instrumental role in managing and optimising living spaces, integrating the indoor-outdoor relationship within the concept of comfort while supporting public and environmental safety and health.

Methodological approach

The methodology plays a central role in this study, relying on interdisciplinary dialogue within

the working groups involved in Spoke 6 of VITALITY, the acquisition and interpretation of urban and climatic data, and the design process as an opportunity to experiment with solutions through which the outcomes of the adopted strategies can be critically assessed.

The research – whose field operational phases are scheduled to commence by the end of 2025 – focuses on three distinct urban contexts in Central Italy, specifically in the Marche Region, encompassing both consolidated urban fabrics and newly developed areas characterised by different building densities: San Benedetto del Tronto, Pagliare del Tronto (a district of the Municipality of Spinetoli), and Ascoli Piceno. While each of these study areas within the central Adriatic region has its specific characteristics, they also exhibit generalisable traits (Figure 2) (20).

The Periadriatic sector of the Marche-Abruzzo Regions is historically characterised by a temperate sub-littoral climate, gradually transitioning to more continental features in inland valley areas. Mean annual temperatures generally range between 12.5°C

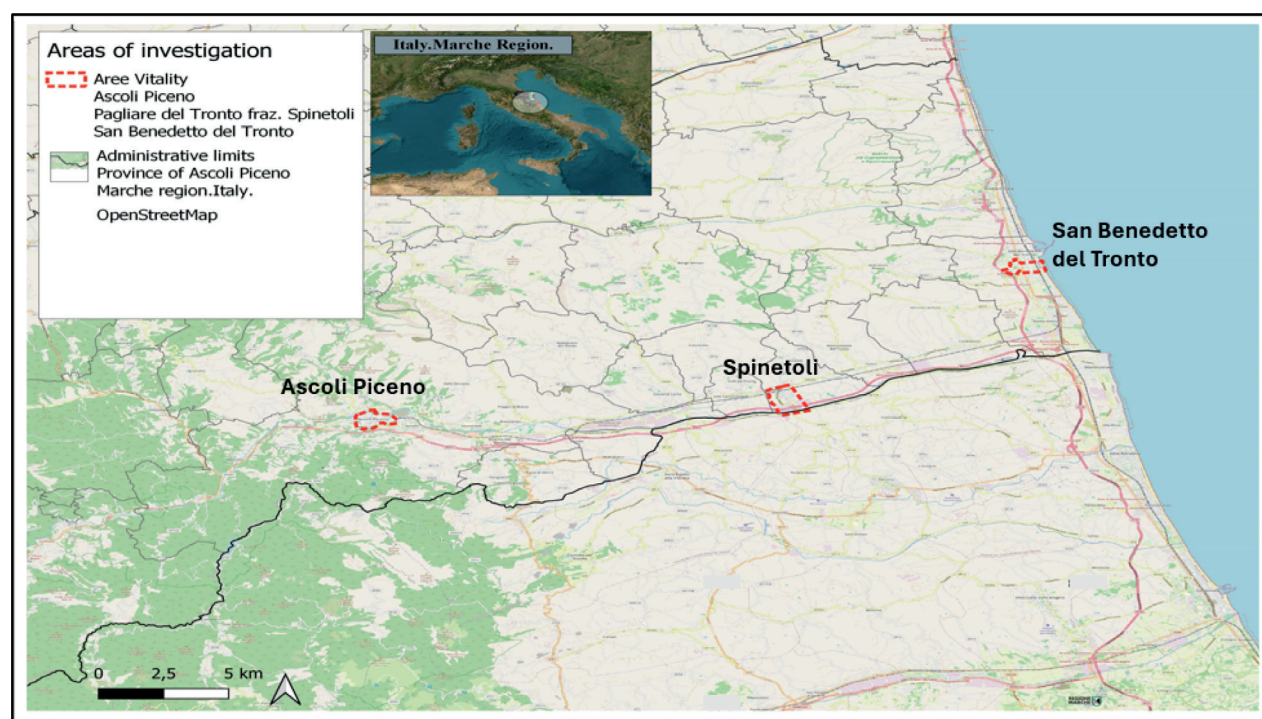


Figure 2. Territorial Framework of the three study areas in Central Italy (Marche Region, Province of Ascoli Piceno), namely Ascoli Piceno, Pagliare del Tronto (district of the Municipality of Spinetoli), and San Benedetto del Tronto.

and 15.5°C, with annual thermal excursions up to 19°C and a vertical thermal gradient of approximately 0.54°C per 100 meters. Annual precipitation usually varies from 600 mm along the coast to 1000 mm in the foothills, with a sub-littoral rainfall regime showing peaks in autumn (November) and secondary maxima in spring (21). Although prolonged summer droughts are rare, the last decade has seen an increasing frequency of extreme rainfall events, as indicated by daily precipitation nearing 100 mm and hourly rates exceeding 30 mm, pointing to a growing erosive potential of meteorological waters even in previously stable areas.

These observations are consistent with the Regional Climate Change Adaptation Plan (PRACC) of the Marche Region (22), which reports an ongoing warming trend (+0.4°C per decade) and projects a further increase of +1.8°C by 2050, with summer peaks of up to +3°C. The plan also anticipates a 10–12% reduction in annual precipitation, with a substantial summer decrease of 38% and a growing occurrence of extreme events (heatwaves, prolonged dry spells, intense spring rainfall). Combined, these studies depict a climate trajectory marked by progressive warming, increasing summer aridity, intensified extreme events, and heightened hydrogeological vulnerability, underscoring the need for localised and data-driven climate adaptation strategies.

The typological and morphological analysis of the study areas has allowed for the identification of insights into the recognition of the formal structure, which converges in the extensive study of Local Climate Zones. These zones analyse the most relevant urban data related to climate change. The climatic investigations are shedding light on meteorological variables, parameters linked to the perception of comfort, as well as challenges and fluctuations across the seasons, all of which are also associated with the specific context of each area (20).

Environmental monitoring

The monitoring of a series of environmental parameters will be conducted through the installation of six data acquisition and processing stations, three of which will be positioned in indoor environments and three in outdoor environments, with two stations

dedicated to each sample area. In the case study of the city of Ascoli Piceno, the indoor sensors will be located at the headquarters of the Cassa di Risparmio di Ascoli Piceno (CARISAP), at Corso Trento e Trieste, 18 (Google Maps coordinates 42.85469881506N, 13.57651783262E), as will the outdoor sensors, which will be installed on the roof terrace of the same building. Regarding the study area of Pagliare del Tronto, the designated location for the outdoor sensors will be Piazza Kennedy (Google Maps coordinates 42°52'07.7"N 13°46'06.8"E), while the indoor sensors will be placed at the Demographic and Tax Services Office, situated within the municipal building (Google Maps coordinates 42°52'06.6"N 13°46'07.6"E). For the study area of San Benedetto del Tronto, the indoor sensors will be positioned in an internal room of the municipal building, currently under verification, while the outdoor sensors will be installed on the roof of the same structure (Google Maps coordinates 42°56'37.2"N 13°52'59.7"E) (Figure 3).

The selection of sensor locations within the three study areas was based on environmental, infrastructural, and functional criteria, consistent with the overarching research objectives. In particular, sites were identified by evaluating specific building characteristics, such as the availability of existing cabling systems, electrical load capacity, and compliance with safety standards, to ensure operational reliability and safeguard both the equipment and its users. Moreover, priority was given to public spaces or areas with high levels of urban attendance, to enable continuous monitoring of real-world exposure conditions and enhance the relevance and applicability of the collected data.

Utility development

The project's field operational phases will start by the end of 2025 and will involve the installation of sensors specifically designed for monitoring the climatic-environmental components (Table 1), integrated with a cloud-based system dedicated to data collection, processing, and transmission.

Concurrently, a specific utility intended for users of the study areas will be developed. This application, equipped with an intuitive and accessible interface, will provide immediate feedback on

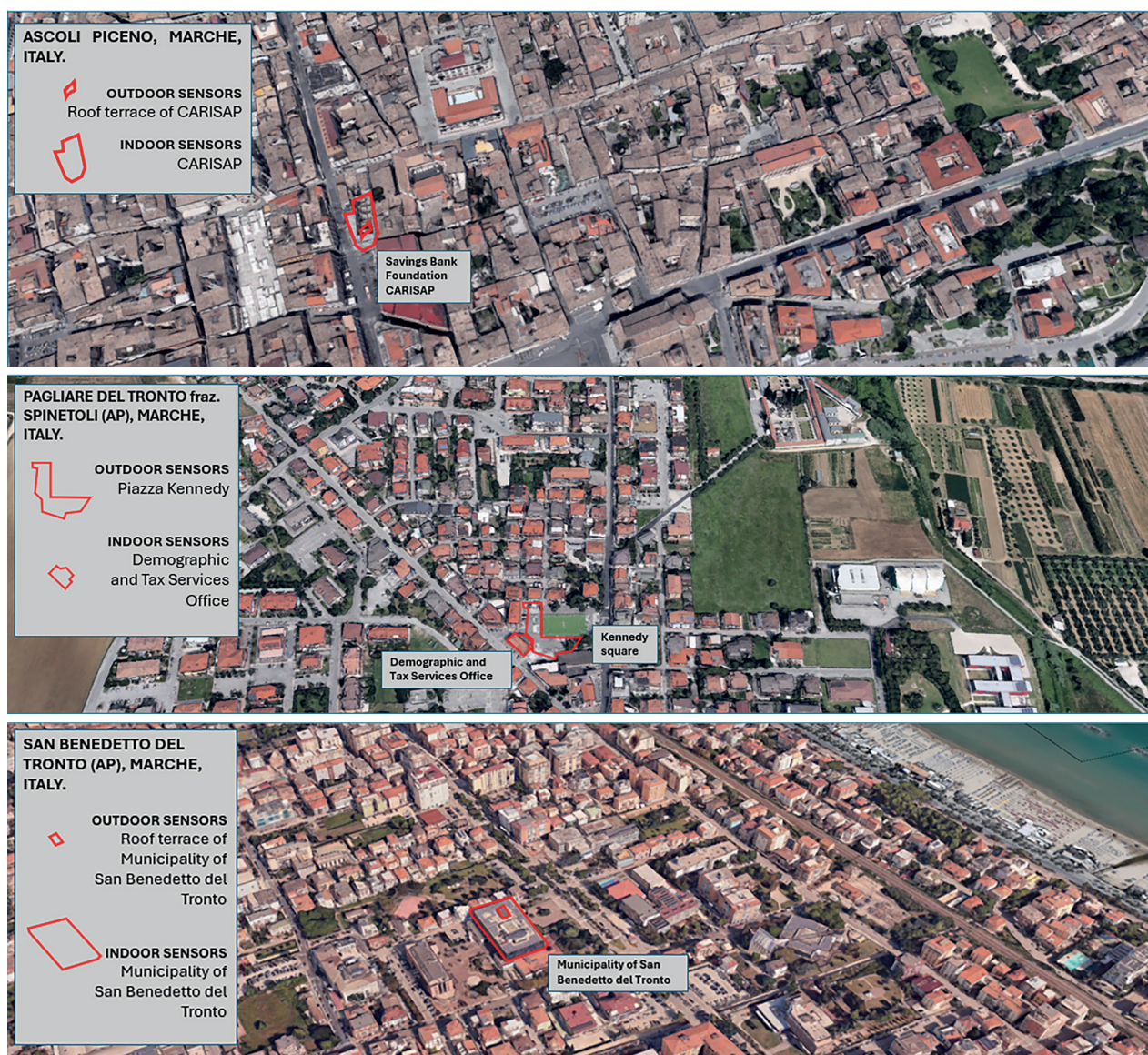


Figure 3. Monitoring stations dedicated to each sample area (Ascoli Piceno, Pagliare del Tronto – district of Spinetoli, San Benedetto del Tronto).

climatic-environmental parameters through real-time updates, enabling users to interpret the collected data and become aware of the specific indoor and outdoor conditions of the monitored sites. Users will also be able to provide information regarding their activities at that moment and the clothing they are wearing. Additionally, the utility will allow users to access further insights on the topics covered and specific guidelines.

The use of the application will be subject to the acquisition of informed consent from users. All data collected will be processed in full compliance with the current data protection regulations, according to Legislative Decree 30 June 2003, n. 196 (Personal Data Protection Code) and its subsequent amendments and integrations, as well as Regulation (EU) 2016/679 (General Data Protection Regulation), following the guidelines issued by the Italian Ministry of Labour and Social Policies.

Table 1. Indoor and outdoor sensors

INDOOR		
Sensor	Measurement	Unit
Thermo-hygrometer	Air temperature and relative humidity	°C, %RH
Globe thermometer	Mean radiant temperature	°C
Air velocity sensor	Indoor air velocity	m/s
VOC sensor	Volatile organic compounds concentration	ppb
PM1, PM2.5, and PM10 sensors	Fine and coarse particulate matter concentration	µg/m ³
CO ₂ sensor	Carbon dioxide concentration	ppm

OUTDOOR		
Sensor	Measurement	Unit
Albedometer	Reflectivity (Albedo)	(W/m ²)
Thermo-hygrometer	Air temperature and relative humidity	°C, %RH
Globe thermometer	Mean radiant temperature	°C
Micro barometer	Atmospheric pressure	hPa
Wind speed sensor	Wind speed	m/s
Wind direction sensor	Wind direction	Degrees (°)
Tipping bucket rain gauge	Precipitation amount	mm
Illuminance transmitter	Light quantity per area	Lux
Luminance transmitter	Perceived brightness	cd/m ²
PAR radiometer	Photosynthetic activity	µmol/m ² /s (400-700 nm)
CO ₂ sensor	Carbon dioxide concentration	ppm
NO ₂ sensor	Nitrogen dioxide concentration	ppb or µg/m ³
SO ₂ sensor	Sulfur dioxide concentration	ppb or µg/m ³
PM2.5 and PM10 sensors	Fine and coarse particulate matter concentration	µg/m ³
VOC sensor	Volatile organic compounds concentration	ppb

Data management

The integration of sensors in indoor, outdoor, and microenvironmental settings enables real-time data collection on key climatic-environmental variables, facilitating the analysis and interpretation of environmental conditions. Environmental monitoring through sensor technology represents a core component of research aimed at enhancing the quality of life and minimising risks to physical and mental health.

The data acquired from the sensors will be recorded daily on an hourly basis and transmitted in real-time with a 60-minute update frequency to a

dedicated digital platform developed within the VI-TALITY project, Spoke 6. This platform will play a key role in data processing and management, enabling direct reading and monitoring of individual measured variables and their combined analysis in relation to the calculation of the Predicted Mean Vote (PMV) thermal-hygrometric comfort index. Subsequently, the processed information will be transmitted to a free-ware application designed for users (in indoor study environments), featuring an accessible interface for visualising and interpreting environmental data, allowing users to interact with it. In this context, the application will be developed by a company selected

through a collaboration call under the VITALITY Spoke 6 project.

In the application, deviations from threshold values (referred to indoor environments) (Table 2) will be assessed and reported using the following colour-coded indicators:

- **Green:** The recorded value falls within the optimal range;
- **Yellow:** The recorded value slightly deviates from the optimal range;
- **Red:** The recorded value significantly deviates from the optimal range.

In cases of non-optimal values, the utility will provide evidence-based recommendations to mitigate health risks specific to the given context. Additionally, users will be able to access relevant institutional websites through dedicated links within the application.

Furthermore, data regarding metabolic activity and clothing will be directly entered by users through a simple guided questionnaire, utilising standardised images (23) (Figure 4). Each image corresponds to a numerical value, which, when selected, will be incorporated with the other variables mentioned above into the PMV calculation formula for the thermal comfort assessment for the specific environments under investigation in the experimental study (University of California, Berkeley, available at <https://comfort.cbe.berkeley.edu/>).

Thermal comfort has been defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as “*the condition of mind that expresses satisfaction with the thermal environment*” (23). Based on this definition, a specific space can be considered thermally comfortable if the occupants feel neutral, do not wish to change the thermal environment, or directly regard the thermal environment as thermally comfortable or acceptable.

Factors that directly influence thermal comfort include characteristics of the occupants, such as metabolic rate (M , expressed as *met*) and clothing insulation (I , expressed as *clo*) and environmental conditions, such as air temperature (T_a , °C) radiant temperature (T_r , °C) air speed (v , *m/s*) and humidity (RH, %) (23). Traditionally, indoor thermal comfort is assessed using

PMV index, which aims to predict the mean value of votes of a group of occupants on a seven-point thermal sensation scale (+3 = hot; +2 = warm; +1 = slightly warm; 0 = neutral; -1 = slightly cool; -2 = cool; -3 = cold), and Predicted Percentage of Dissatisfied (PPD) index, which estimates the percentage of thermally dissatisfied occupants of an environment (23,24).

Expected results

This multidisciplinary, technology-based and interactive monitoring approach will significantly contribute to the project objectives. Data obtained from the installed sensors will provide details about climatic-environmental variables, allowing researchers to monitor the study areas over time and compare them spatiotemporally. Moreover, the integration of such data with a specifically designed user-friendly utility will enable users – and public institutions and private citizens, as well – to develop a greater awareness of living spaces, promote their responsible use, and, long-termly, safeguard and promote their well-being and health.

Indeed, the application is intended to be potentially accessible to all users and will not be limited to individuals affiliated with the selected pilot areas. In case of non-local users, they will be able to use it and get the same information by just filling in specific climatic-environmental data manually.

Users will be able to download the utility either via a direct link or by scanning a QR code, ensuring ease of access and facilitating broader engagement and widespread dissemination of the tool.

Discussion and conclusions

Urban Health is a developing discipline involving several research, education, and policy-making areas. It refers to a strategy that integrates actions to protect and promote health in urban planning, emphasising the connections between physical, psychological and social well-being and the urban environment.

According to the World Health Organization (WHO), health “...is a state of complete physical, mental

Table 2. Individual indoor parameter ranges and health outcomes

Individual parameter	Temperature (T)	Notes	Health effects from deviations	Bibliography
Indoor temperature	T < 16°C T < 12°C T < 9°C	Indoor temperatures below 16°C can decrease resistance to respiratory infections, while temperatures below 12°C can cause increased blood pressure and other cardiovascular problems. Deep body temperature typically remains stable in elderly individuals when clothed and at rest, unless exposed to an ambient temperature of 9°C or lower for a duration of two hours or more.	Dehydration. Cardiovascular diseases, respiratory symptoms (such as shortness of breath, regardless of aetiology), flu-like symptoms, morning catarrh, mental stress, effects on empathy and positive affect, daytime sleepiness, an inverse relationship between systolic and diastolic blood pressure and core body temperature. The absorption of insulin doses in individuals with insulin-dependent type 1 diabetes significantly increases with rising core body temperature. Worsening of schizophrenia symptoms. Increased agitation and restlessness in elderly individuals with dementia residing in nursing homes. Elevation of core body temperature. In the elderly, gait speed, the ability to rise from a chair, balance maintenance, and walking distance are significantly reduced as core body temperature increases. For every 1°C increase above the baseline temperature (18°C), a 2.1% rise in overall cardiovascular disease-related mortality has been observed. Suboptimal temperatures are associated with a significant mortality burden. Associated heat stress may increase morbidity, contribute to adverse pregnancy outcomes, and negatively impact mental health. Severe heat stress can also reduce physical work capacity, impair motor and cognitive performance, negatively affect productivity, and increase the risk of occupational health issues.	(5,16,25–37)
	≥ 18°C	Optimum. Refers to healthy adults in the sedentary phase living in countries with temperate or cold climates.		
	20.5 < T < 24°C	Optimum. For countries with temperate or cold climates. Necessary for vulnerable groups, such as the elderly, children, and people with cardiorespiratory diseases.		
	26 < T < 32°C	Heat stroke risk (associated with high relative humidity and no ventilation).		
	T > 32°C	In countries with temperate or cold climates, this has been identified as a range for probable health problems.		
Indoor relative humidity (% RH)	Relative humidity (%RH) 40% < RH < 50%	Notes Optimal range in most cases. The presence of humidity consistently outside the optimal range is demonstrated by the visible presence of mould or moisture stains on walls and interior objects with suitable substrates and in the presence of low general hygiene.	Health effects from deviations Respiratory symptoms: cough, phlegm, wheezing, asthma. Increased biological contaminants produced by fungi, mites and moulds. Increased incidence of respiratory tract infections with loss of upper airway osmolality. Instability and aggravation of ocular tear film physiology. Decreased air quality and dispersion of volatile organic compounds (VOCs). Respiratory disorders, such as wheezing, asthma, persistent cough, wheezing, rhinoconjunctivitis, and eczema, can often be explained by exposure to mould or household humidity, especially in the early years of life. Infectious symptoms: fungal and bacterial infections in immunocompromised individuals. Toxic symptoms: symptoms from exposure to mycotoxins produced by specific moulds. Neurological/behavioural symptoms (Sick Building Syndrome): headache, anxiety, difficulty in concentrating, insomnia. Allergic symptoms: rhinitis, dermatitis, allergic alveolitis.	(6,37–39, 39–43)

Table 2 (Continued)

Individual parameter	Relative humidity (%RH)	Notes	Health effects from deviations	Bibliography
	RH < 20-30%	Air perceived as dry, feeling of dryness in the eyes and respiratory tract. Common in environments with reports of complaints about air quality. Frequent in many indoor conditions (difficult to rise above 30-40% in winter).	Increase in eye and respiratory tract irritation, deterioration of tear film stability, acute ocular and airway symptoms in office environments, reduced immune defence efficiency, and decreased work productivity. Increase in symptoms typical of "Sick Building Syndrome" and worsening of ocular parameters (<i>e.g.</i> , precorneal tear film stability).	
	30 – 40%	Range at which symptoms related to dryness begin to decrease.	Reduction in dryness-related symptoms, but an increase in the perception of "stale air" or odours.	
	40 – 45%	Recommended range by many sources for comfort and health. Recommended level to prevent dust mite growth.	Relief of respiratory and ocular symptoms, improvement in perceived air quality.	
	45 – 50%	It tends to be protective for ocular and respiratory health.	Further reduction in dryness-related symptoms; however, the perception of "stale air" may begin to increase.	
	> 50%	High humidity, in some cases, excessive.	Potential increase in the perception of "stagnant air"; increase in odours and VOCs from building materials. The threshold limit for the proliferation of fungi and moulds in building materials and in the presence of suitable substrates.	
	> 60%	Difficult to maintain in cold environments; risk of condensation.	Potential issues with mould and structural humidity; possible increase in pathogens and allergens with the proliferation of fungi, lichens, moulds, and dust mites. Asthma, allergic alveolitis, infections in immunocompromised individuals, multisystemic diseases from mycotoxins, and symptoms of SBS.	
Individual parameter	Ventilation	Notes	Health effects from deviations	Bibliography
Indoor ventilation	0.1 – 0.15 m/s	Stagnant air. If excessive, the sensation of "still" or "too stagnant" air; desire for more air movement (≤ 0.2 m/s). Air-conditioned offices (ISO 7730 standard).	No direct health effects reported; potential thermal discomfort. To avoid "draught" discomfort (air drafts) in cool environments.	(44-49)
	0.2 m/s	Air movement in air-conditioned buildings was initially strictly controlled below 0.2 m/s to avoid the risk of drafts. ASHRAE 55 standard – ventilation $\leq 0.2 - 0.3$ m/s in neutral or cool conditions. Ventilation $\leq 0.2 - 0.3$ m/s for work in cold environments to prevent discomfort from convective cooling, especially in the head, neck, and hands.	The threshold limit to avoid "draught" discomfort (air drafts) in cool environments.	
	0.3 m/s	Considered acceptable in relation to indoor and outdoor temperatures between 21 and 26°C. The threshold beyond which discomfort from air drafts (draught) is perceived in cool environments, especially if the individual has a cool thermal sensation.	No direct health effects reported.	

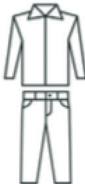
	0.45 m/s	"Just right" to "slightly breezy"; maximum perceived satisfaction in relation to indoor and outdoor temperatures between 21 and 26°C.	No direct health effects reported.	
	0.6 m/s	Possibility of slight increase in thermal discomfort due to "excessive ventilation" in relation to indoor temperatures of 21/23.5/26°C and outdoor temperature of 26°C.	In limited cases, localised sensations of dryness (eyes/nose).	
	0.75 m/s	Considered acceptable only with outdoor temperatures above 26°C. Regarded as "slightly breezy" or "too breezy" in other cases. ASHRAE 55 standard in hot environments, air velocity considered pleasant up to 0.8 m/s with personal control.	Possible mild discomfort such as dry eyes/nose/mucous membranes, but not severe.	
	0.9 m/s	Perceived by many as "too ventilated"; increase in dissatisfied individuals. Promotes body heat dissipation and the expulsion of pollutants and CO ₂ .	Possible localised discomfort (e.g., dryness of mucous membranes), but health effects are negligible in the short term.	
	0.6 – 1.6 m/s	Hot and humid environments (e.g., Brazil, Thailand). To improve comfort and reduce the use of air conditioning.		
	> 1.5 m/s	Effective only if the user has direct control. Perceived as a natural, "soft" wind. Perceived as comfortable in relation to high temperatures > 28°C in temperate/cold climates. Efficient in removing heat and local pollutants. Supports the "wash-out" effect in humid environments.	Possible undesirable effects such as dry eyes and skin irritation. Not recommended in sensitive environments or for prolonged use.	
	0.5 vol/h	Ensure adequate ventilation to prevent air stagnation, alteration of microclimatic parameters, and to facilitate the removal of potential toxic or harmful substances and volatile organic compounds (VOCs)		
Individual parameter	Volatile Organic Compounds (VOCs)	Notes	Health effects from deviations	Bibliography
Concentration of volatile organic compounds (VOCs)	< 0.2 mg/m ³	Considered acceptable within the limits of combinations between different VOCs or specific individual compounds.	Some classes of VOCs, even at low concentrations, can cause irritative effects on ocular tissues and the upper respiratory tract. Formaldehyde: Concentrations of 10–20 ppm or 0.1 mg/m ³ can cause coughing, a sense of pressure in the head, palpitations, and chest tightness. Toluene: Increases of 1 µg/m ³ are associated with an increased risk of asthma (RR = 1.02). Benzene: Each increase of 1 µg/m ³ is associated with an increased relative risk of leukaemia (RR = 1.03) and low birth weight (RR = 1.12). VOCs are implicated in the onset of SBS. Many VOCs are considered harmful to ecosystems and toxic and/or carcinogenic to human health with prolonged exposure over time.	(6,50–54)

Table 2 (Continued)

Individual parameter	Volatile Organic Compounds (VOCs)	Notes	Health effects from deviations	Bibliography
	0.3 mg/m ³ (guideline value for Total Volatile Organic Compounds – TVOC)	Proposed guideline value for indoor exposure.	Exceedances linked to mild symptoms and the onset of discomfort.	
	0.2 – 3 mg/m ³	Possible onset of symptoms in sensitive individuals.	The onset of SBS symptoms, such as sensory irritation, headache, and fatigue.	
	1 mg/m ³	In the cited studies, detected in 6.8% of cases of personal exposure.	Associated with high exposure during car journeys, potential cumulative systemic risk.	
	1 – 3 mg/m ³	Typical range of TVOC in indoor environments.	Accumulation from multiple sources (furniture, cleaning products); possible discomfort or subacute effects	
	2 mg/Nm ³ (for emissions ≥ 10 g/h) refers to the sum of the masses of individual VOCs.	Carcinogenic, mutagenic, or reprotoxic VOCs. Obligation to replace with less harmful substances.	Carcinogenicity, mutagenesis, reproductive toxicity.	
	> 3 mg/m ³	TVOC. Very likely effects.	High probability of discomfort, irritation, subacute neurological disturbances, and possible systemic effects.	
	20 mg/Nm ³ (for emissions ≥ 100 g/h) refers to the sum of the masses of individual VOCs.	Halogenated VOCs with specific risks. Obligation to always direct the emissions.	Possible carcinogenic effects, genetic damage.	

Individual parameter	PM ₁ , PM _{2.5} e PM ₁₀	Notes	Health effects from deviations	Bibliography
Particulate Matter 2.5 (PM _{2.5})	5 µg/m ³	Recommended by the WHO guidelines for the annual value.	Cardiopulmonary disorders. Association with respiratory diseases, including asthma, chronic bronchitis, and acute bronchitis. PM is linked to a range of negative effects, including cardiorespiratory mortality and morbidity. Long-term exposure to PM has been most strongly associated with mortality attributable to ischemic heart disease, arrhythmias, heart failure, and cardiac arrest. For every 10 µg/m ³ increase in PM _{2.5} levels, the risk of death increases by 8% to 18%. Fine particulate matter exposure is a risk factor for cause-specific cardiovascular mortality through mechanisms likely including pulmonary and systemic inflammation, accelerated atherosclerosis, and alteration of cardiac autonomic function. Carcinogenic to humans.	(55–66)
	15 µg/m ³	Recommended by the WHO guidelines for the daily value.		
	25 µg/m ³	Italian Legislative Decree 155/2010		
	15 µg/m ³	Recommended by the WHO guidelines for the annual value.		
	45 µg/m ³	Recommended by the WHO guidelines for the daily value.		
	40 µg/m ³	Italian Legislative Decree 155/2010, for annual values.		
Particulate Matter 10 (PM ₁₀)	50 µg/m ³	Italian Legislative Decree 155/2010, for the daily value.		
Individual parameter	CO ₂	Notes	Health effects from deviations	Bibliography
Carbon dioxide (CO ₂)	< 1000 ppm	600 ppm: optimal value. Acceptable indoor air quality. Standard threshold for adequate ventilation.	No adverse effects expected.	(67–70)
	1000 – 2000 ppm	Insufficient ventilation. Common levels in overcrowded classrooms and offices.	Fatigue, headaches, reduced concentration. Cognitive effects: Controlled studies have demonstrated that CO ₂ concentrations around 1000 ppm can impair decision-making performance, with more pronounced cognitive decline at 2500 ppm.	
	2000 – 5000 ppm	Poor air quality. Indicator of severely inadequate ventilation.	Drowsiness, increased heart rate, cognitive performance decline.	
	> 5000 ppm	Hazardous levels. Occupational exposure limit for an 8-hour workday.	Hypercapnia, nausea, mental confusion. Visual disturbances and tremors. Loss of consciousness.	
	380 – 500 ppm	Typical concentration in urban outdoor environments	No adverse effects expected.	

Which ensemble best matches what you are wearing right now?

				
☐	☐	☐	☐	☐
				
0.2 clo	0.4 clo	0.5 clo	0.6 clo	1.0 clo

What is your activity level right now?

				
☐	☐	☐	☐	☐
0.8 met	1.1 met	1.2 met	1.7 met	3.8 met

Figure 4. Thermal environment point-in-time survey concerning clothing insulation and metabolic activity data (source: ASHRAE Standard 55-2023 – Thermal Environmental Conditions for Human Occupancy, informative appendix H: Comfort Zone Methods).

and social well-being...” and “...is created and lived by people within the settings of their everyday life; where they learn, work, play and love” (71,72). These definitions strongly include several social and environmental determinants of health, such as climate and living conditions, as well as working, economic, social, and cultural aspects of life. In this context, it is essential to consider the urban outdoor and indoor areas as potential promoters of health, as the quality of life of populations also depends on the state of such environments (73).

Social, climatic and sanitary dynamics contributed to the “Indoor Generation” phenomenon, with people spending up to 90% of their daily time in indoor environments. Therefore, it is quite clear that studying

living environments and the microclimatic variables plays a key role in a public health context.

However, despite the extensive supporting literature and the technical and technological advancement for the implementation of monitoring systems (including low-cost systems with general-purpose accuracy) for indoor environmental quality (74,75), these control strategies lag their available potential.

Providing data of this kind would enable the Decision Support System to validate actions and act on time to optimise resources and public welfare, and health.

The implementation of utilities for electronic devices, based on the processing of environmental data

collected in real time from lived spaces, enables users to develop a greater awareness of living spaces, promoting their responsible use, also through a holistic approach to the relationship between humans and the environment. Such utilities, by fostering the understanding of one's safety and well-being, contribute not only to the improvement of individual health but also to ecological progress in the surrounding context, enhancing clarity between indoor and outdoor dynamics, and their relationship to the health of the occupants.

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