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Urban Cycling Lab: A citizen science protocol for assessing and reducing exposure to environmental stressors among bike commuters

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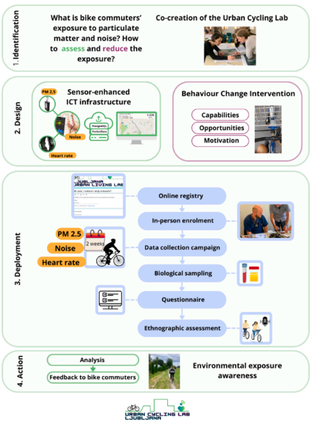
GRAPHICAL ABSTRACT

Overview of the citizen science protocol for assessing and reducing exposure to environmental stressors among bike commuters.



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ABSTRACT

Bike commuters are regularly exposed to environmental stressors that impact their health and well-being. The Urban Cycling Lab in Ljubljana, developed within an Urban Living Lab and

Related research articlenone
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citizen science framework, engaged stakeholders in assessing exposure to particulate matter and noise, and in co-creating strategies to reduce it.

This citizen science intervention combined sensor-enhanced ICT tools with behaviour change theory to assess both environmental and behavioural aspects of exposure. Exposure assessment included low-cost personal sensors as well as chemical analysis in biological samples to evaluate environmental exposure, while biochemical analysis of biological samples aimed to evaluate potential biological effects of exposure. Participants collected data using portable sensors and accessed real-time exposure comparisons via the *Route Exposure Comparator* web app. Biological samples (peripheral blood and spot urine) were collected from each participant at the end of data collection period.

Data on sociodemographic characteristics, commuting habits, and environmental health literacy were collected via questionnaires. Ethnographic methods captured participants' perceptions, route choices, and the intervention's influence on commuting behaviour.

This paper presents the methodology used to implement this intervention and provides a transferable model for participatory environmental exposure assessment.

- Designed and implemented a citizen science intervention to assess cyclists' exposure to air pollution and noise using sensor-enhanced ICT tools.
- Promoted environmentally informed route choices through behaviour change strategies and digital feedback.
- Applied survey and ethnographic methods to explore commuting behaviours and intervention impact.

Specifications table

Subject area	Environmental Science
More specific subject area	Urban environmental exposure, citizen science, and active mobility
Name of your protocol	Urban Cycling Lab: a citizen science protocol to assess and reduce bike users' exposure to environmental stressors
Reagents/tools	Atmotube Pro (Atmotube, ATMO®) – for particulate matter monitoring NoiseCapture App (CNRS, Université Gustave Eiffel) – for noise exposure mapping Fitbit Charge 6 (Google LLC) – for physiological data monitoring Dayton Audio iMM-6 Microphone with VOLTCRAFT SLC-100 Calibrator – for accurate noise measurement Primerjalnik.si – (translated as *Route Exposure Comparator*) custom web application for real-time exposure data visualization PostgreSQL/PostGIS, PocketBase – for data storage and management
Experimental design	A theory-driven citizen science intervention involving bike commuters in Ljubljana, combining low-cost sensors, digital tools, and behaviour change strategies to assess and reduce exposure to particulate matter and noise during cycling.
Trial registration	Not applicable
Ethics	The study was approved by the Commission for Medical Ethics at the Ministry of Health of the Republic of Slovenia (approval number: 0120–323/2023/6). All participants provided written informed consent in accordance with the approved protocol.
Value of the Protocol	• Implements a technology-enabled citizen science approach to engage bike commuters in monitoring personal exposure to air pollution and noise. • Integrates behaviour change theory to promote environmentally informed route choice, enhancing individual-level environmental health literacy. • Offers a replicable, scalable methodology for participatory environmental exposure assessment and urban mobility planning.

Background

Urban cycling is increasingly promoted for its environmental and health benefits, including reduced greenhouse gas emissions, improved cardiovascular health, and more sustainable urban transport [1]. However, cyclists are often exposed to environmental stressors such as air pollution, noise, and heat in dense urban microenvironments. These exposures have raised concerns about potential health risks, particularly when commuting through high-traffic corridors [2,3]. Exposure levels are known to vary significantly depending on route choice, traffic density, and meteorological conditions.

Efforts to reduce cyclists' exposure to environmental stressors often involve recommending alternative routes through less congested or greener areas [1]. Yet, implementing such recommendations at scale is challenging due to infrastructural limitations, political constraints, and competing urban mobility priorities [1,4]. Furthermore, individual-level exposure data are rarely integrated into policy or planning, despite the potential of personalized data to guide safer, healthier mobility decisions.

Urban Living Labs (ULLs) have emerged as promising platforms for testing and co-developing innovative urban solutions [5]. They involve multiple stakeholders—residents, researchers, public authorities, and private sector partners—in real-life settings. Their user-centred approach can contribute to tackling urban sustainability challenges by building a sense of ownership among local stakeholders and encouraging uptake of results into policy change [6]. Despite this potential, sustained and meaningful citizen involvement remains difficult to achieve in practice, and methodological approaches for enabling it are still evolving [7].

Citizen science provides a complementary approach to ULLs by enabling structured, participatory research processes. In citizen science projects, community members actively contribute to data collection, interpretation, and sometimes decision-making [8,9]. When enhanced by digital tools, citizen science methods can generate real-time, high-resolution environmental data that are geo-referenced and personalized [10,11]. These data can support both individual decision-making—such as changing commuting routes—and system-level urban planning processes [12,13].

The integration of behaviour change theory into citizen science adds an important dimension, as it links data collection with learning and action [13,14]. By engaging participants as both data collectors and data users, it is possible to encourage reflection and awareness about environmental exposures and to support informed choices, such as selecting lower-exposure commuting routes. This approach also offers opportunities to embed local knowledge and lived experiences into urban policy discussions.

In addition to the sensor-based exposure assessment, this protocol includes the analysis of human biological specimens, such as blood and urine, to detect and quantify chemicals and their metabolites, to provide a more accurate estimate of individual body burden and individual's response to exposure (e.g., oxidative stress biomarkers). This human biomonitoring approach can complement environmental data and strengthen evidence for communicating health risks to participants, thereby supporting behaviour change and enhancing the policy relevance of findings [15].

This protocol describes the methodological design of the Ljubljana Urban Cycling Lab (UKLL), a citizen science initiative embedded within a ULL framework and supported by the URBANOME H2020 project. The UKLL was implemented by an interdisciplinary team of researchers in Ljubljana, Slovenia, and was designed to assess bike users' exposure to air pollution and noise through sensor-based data collection, complemented by human biomonitoring, behavior change, and ethnographic methods. It involved collaboration with local stakeholders across sectors and applied digital tools to support individual and collective interpretation of exposure data.

The protocol is intended to serve as a replicable model for citizen science-based environmental exposure assessments and mobility research in urban settings.

Description of protocol

Study setting

Situated in a basin between the Alps and the Dinaric mountains, Ljubljana, the capital of Slovenia, is a mid-sized European city with 292,988 inhabitants across 275 km^2 [16], and cycling accounting for 11 % of daily trips [17]. During the last ten years, traffic arteries in the city centre have been transformed into shared space for cyclists, pedestrians and public transport. Promoting cycling as a primary mode of transportation is integrated into the broader framework of the national transportation development plan [17].

The main air pollution sources are traffic emissions and residential heating, which are common among European cities but are exacerbated by Ljubljana's geographical setting. The city experiences thermal inversions, particularly in winter, which trap pollutants near the surface due to weak wind circulation and limited vertical mixing [18]. PM2.5 and NO_2 levels correlate with traffic density, often exceeding target thresholds on high-traffic roads during colder months and at night. Although cyclists in Ljubljana generally encounter lower PM2.5 levels than in other European cities [19], exposure varies spatially and temporally, with pollution levels driven more by meteorological conditions and urban activity than by intra-day fluctuations.

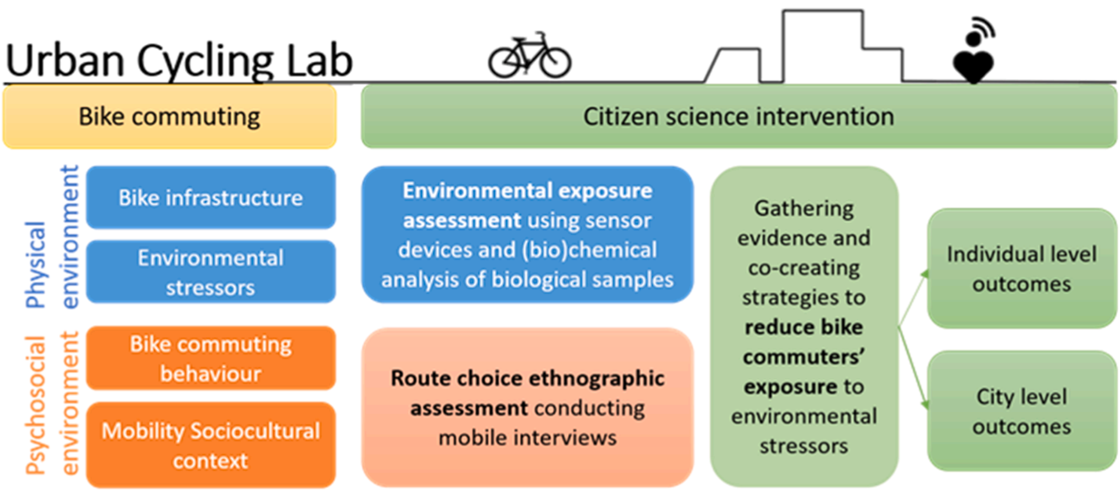


Fig. 1. The Urban Cycling Lab was designed as a citizen science intervention with potential impacts at the individual and city levels to reduce bike commuters' exposure to environmental stressors.

Aims

The aims of the study are the following:

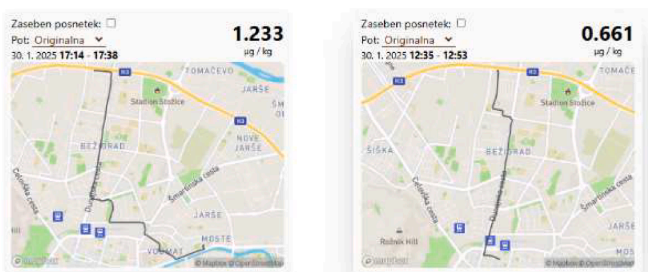
(1) To assess bike commuters' exposure to environmental urban stressors, Particulate Matter and Noise, using low-cost personal sensor devices and (bio)chemical analysis of biological specimens (urine and blood samples) to assess individual environmental exposure and biological response, e.g. oxidative stress.
(2) To co-create strategies to reduce bike commuters' exposure to environmental stressors, Particulate Matter and noise, and provide stakeholders with evidence base for informed decision making to improve bike infrastructure and mobility strategies.

Study design: Citizen science approach

Following the ULL approach, this transdisciplinary study engaged stakeholders in an Urban Cycling Lab to assess bike users' exposure to air and noise pollution on their daily routes and the co-creation of strategies to reduce exposure. Following the quadruple helix model, the project brought together interested stakeholders in the formulation of inclusive and innovative mobility strategies in Ljubljana, including civil society (bike commuters, NGOs), public authorities (local and national decision-makers), researchers, and industry (air pollution experts, bicycle manufacturers, bike infrastructure developers).

This study implemented citizen science methods to comprehensively address elements of the physical (e.g., built and natural environment) and the psychosocial (e.g., active travel behaviour and cultural mobility context) dimensions of bike commuting. The citizen science approach was used as a systematic participatory methodology for simultaneously engaging stakeholders in the environmental exposure assessment and to examine bike commuters' route choice, perceived environmental exposure, and opportunities to reduce exposure to environmental stressors, while promoting behaviour change at the individual and city levels. (Fig. 1). The citizen science protocol followed four phases described below: identification, design, deployment and action [12].

Table 1
Digital tools/sensor-enhanced ICT infrastructure tailored for bike commuters' personal environmental exposure assessment.

Measuring tools	Description
Atmotube 	The Atmotube air pollution monitor continuously tracks air quality parameters and transmits data to a mobile device via Bluetooth Low Energy (LE).
Noisecapture 	Android application that records ambient noise levels, generating acoustic data paired with geocoded locations.
Fitbit 	The device is worn on the wrist, it tracks various physiological parameters such as heart rate, activity levels, and breathing rate.
Route Exposure Comparator (Primerjalnik.si) 	An interactive web-based platform tailored for the autonomous visualization and interpretation of the data. The platform provides insights into individual exposure, and users can explore differences within a day, between different days of the week and, differences in exposure when using different routes.

Identification phase: Co-creation workshop

A co-creation workshop was held on March 5, 2024, to establish the Urban Cycling Lab and explore interventions for reducing cyclists' exposure to environmental stressors. Stakeholders were invited via email, selected for their expertise in urban mobility, environmental health, and cycling advocacy to ensure a multidisciplinary perspective. Ten participants attended, representing public authorities ($n = 4$), civil society organizations ($n = 4$), and academia ($n = 2$). Using the World Café methodology, attendees engaged in thematic discussions on urban cycling challenges, participatory mapping of low-exposure paths, and co-creation strategies. The workshop established the starting point for the UKLL since stakeholders committed to supporting the recruitment of bike users, data dissemination, and policymaking efforts.

Design phase: The urban cycling lab intervention

The team of researchers designed the Urban Cycling Lab theory-driven citizen science intervention. It was tailored as a behaviour change intervention to increase the understanding of bike users' exposure to environmental stressors (environmental health literacy) and promote the adoption of health-protective behaviours to reduce exposure. The behaviour change theoretical approach that informed the intervention was the Capability, Opportunity, Motivation "COM-B" model [20]. A sensor-enhanced ICT infrastructure was tailored to facilitate bike users' engagement in the exposure assessment data collection and interpretation process. Volunteer bike commuters carried sensing devices for two weeks during usual bike commuting in Ljubljana (Table 1), and used a web-based platform to visualize geo-coded real-time exposure levels and explore differences in exposure when using routes of their choice. Participants received a 25-euro gift voucher for bike service, after completing the intervention.

Behaviour change intervention

In behavioural terms, the intervention aimed to promote bike commuting on routes with low exposure to environmental stressors. Following the COM-B model methodology [20], the intervention targeted multiple behavioural components. Psychological capability was addressed by equipping bike commuters with knowledge and digital tools for self-monitoring environmental exposure on different routes. Physical opportunity was enhanced by promoting the exploration of available lower-exposure cycling paths, while social opportunity was fostered by increasing the visibility of other cyclists choosing these routes. To strengthen reflective motivation, the intervention emphasized the well-being benefits of reduced-exposure paths, and automatic motivation was reinforced by encouraging the regular use of these environmentally aware routes.

ICT infrastructure

The Urban Cycling Lab ICT infrastructure integrates multiple digital tools to facilitate data collection, storage, processing, and visualization (Fig. 2). Designed to support both researchers and citizen scientists, this system enables autonomous data analysis while maintaining structured, research-driven analytics (Full details on Suppplement 1). The infrastructure consists of:

- PostgreSQL/PostGIS: A relational database for storing raw, unprocessed sensor data with geospatial processing capabilities.
- PocketBase: A lightweight, self-hosted Backend as a Service (BaaS) for managing merged datasets and user metadata. It supports real-time interaction and serves as the backend for both Route Exposure Comparator Admin and the Web Application.
- Route Comparator Admin Dashboard: A tool that enables researchers to monitor participant records, manage data integrity, and troubleshoot issues.
- Route Comparator Web Application: The primary interface for participants, allowing them to link their sensor data, compare exposure scenarios, and visualize personal environmental data.

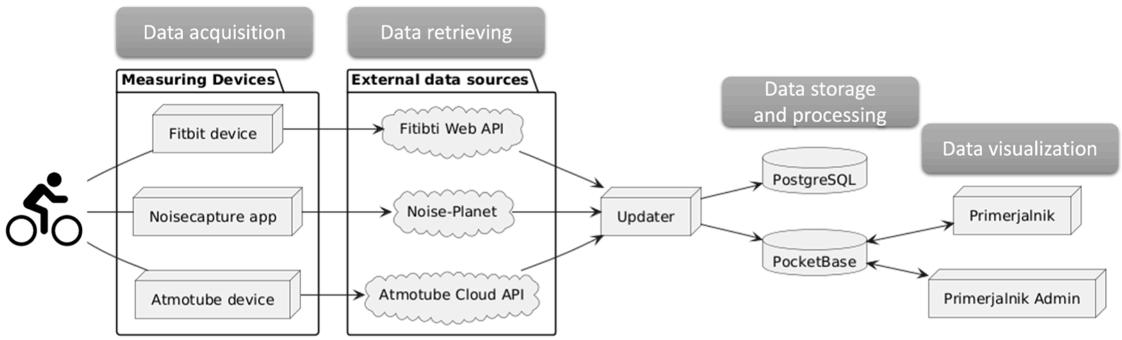


Fig. 2. The data flow in the ICT infrastructure of the Urban Cycling Lab provides a solution for collecting, harmonizing, and visualizing citizen science data, ensuring both researcher-driven analytics and autonomous volunteer participation.

Route comparator web application. The web application serves as the main interface for participants, enabling them to link their sensor data and explore their environmental exposure through interactive visualizations (Fig. 3). To access the web app each participant is randomly assigned a username, ensuring privacy and anonymization of data. Participants can access the merged records and the interactive visualizations showing exposure differences within a day, across multiple days, and between different route choices.

Urban cycling lab participants

Adults (>18 years old) using bicycles as their main mode of commuting in Ljubljana were eligible to participate in the study. The network of multi-sectoral stakeholders from the UKLL collaborated in disseminating the call for volunteers who commute by bicycle in Ljubljana (Fig. 4). The bike users were invited to join the UKLL through word of mouth and social media of the stakeholders, and media channels (radio, podcast).

Interested volunteers filled out an online form (Supplementary information - 2) which included details about the project, the enrolment process, and measurements. Before proceeding with the form, each responder was informed of the specifics of personal data collection and use and was required to agree. The initial section required respondents to confirm their eligibility for the project, i.e., cycling in Ljubljana at least three times per week, provide specifications on their mobile phone (operating system, phone brand, and availability of an AUX jack inlet or adaptor to allow connection with an external microphone). Following this, the respondents were presented with date options to join the data collection campaign (including time requirements and locations to attend project appointments). Only dates for the next 3–5 recruitment sessions were available in the form. Additionally, information on their regular bike routes was collected (indicated through Google Maps), and their willingness to participate in workshops, ride-along interviews, and how well they are able to communicate in English. Participants could choose which routes to assess based on their commuting

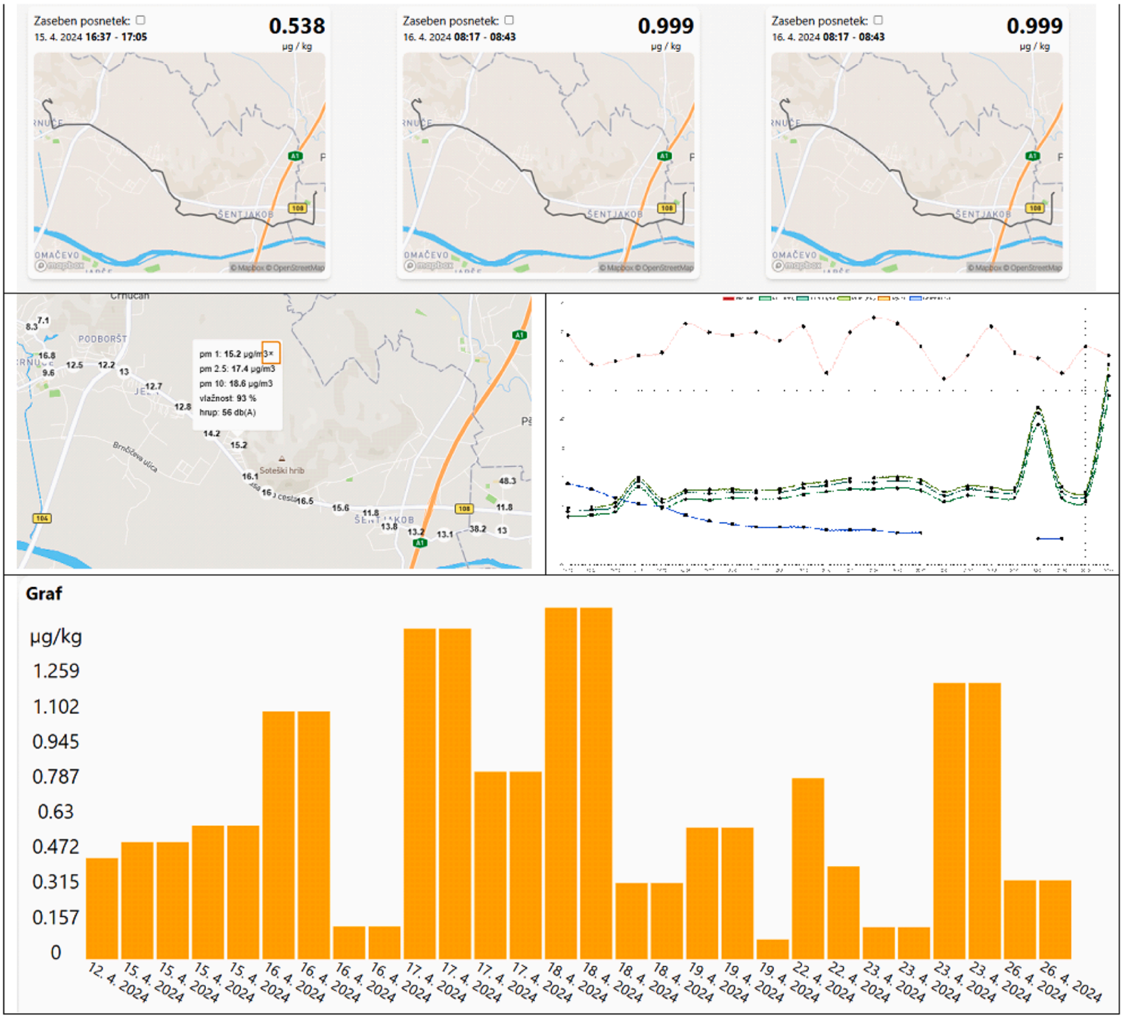


Fig. 3. Example of individual-level exposure data - spatial representation of routes and cumulative dose (top), detailed minute-resolution data presented as a map and chart (middle), and a comparison of cumulative particulate doses for each route by individual participants (bottom). All code used for data processing, analysis, and the digital infrastructure of the Urban Cycling Lab is available upon request.

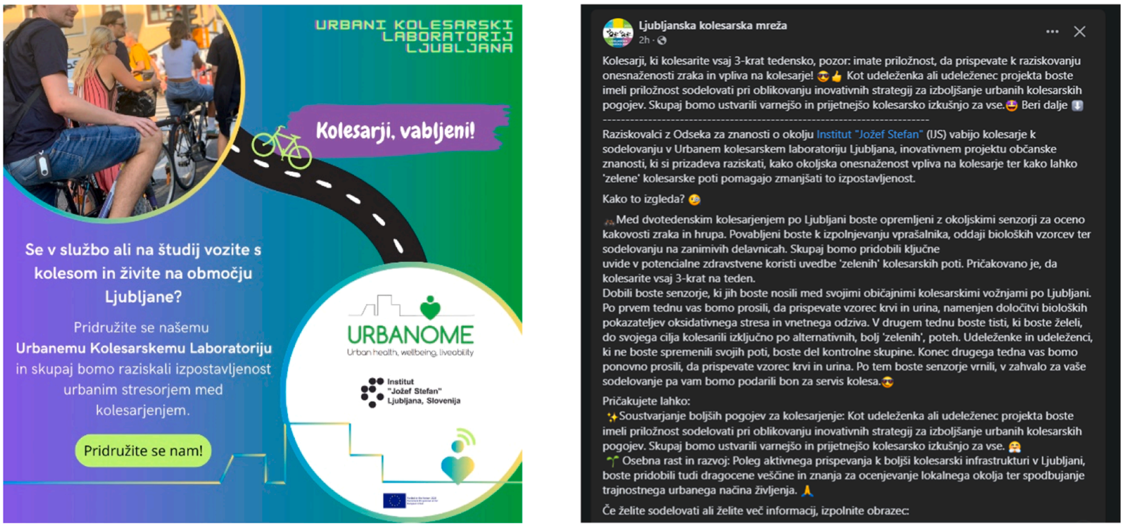


Fig. 4. Urban Cycling Lab dissemination piece posted by stakeholder to promote volunteers' enrolment.

habits and interests.

Deployment phase: Data collection

Starting on 12. April 2024 and ending 25. April 2025, 200 bike users joined the Urban Cycling Lab. Each volunteer attended an individual training session (Supplementary information - 3), where they signed informed consent forms, received measuring devices, and learned how to record environmental parameters and routes. They were trained in using the Atmotube device, the Noisecapture app, and the Fitbit, and were provided with anonymized profiles to access the Route Comparator web-based platform (Primerjalnik.si) and interpret their collected data. Those whose phones were incompatible with project requirements received pre-configured phones with the necessary apps. Ultimately, bike users had the autonomy to select and compare different commuting routes, allowing for an individualized assessment of personal exposure.

Every week, except for holiday periods, a new group of participants ($n = 6$ average) started to collect data. The data collection period suggested per volunteer was two weeks; however, due to meteorological and personal circumstances (weather, health, personal appointments or traveling) there was flexibility to extend. Out of the 238 volunteers who submitted the enrolment form, 212 joined the study and 205 had complete data set.

Communication was maintained through multiple channels (e.g., email, phone calls, newsletter) to ensure transparency, engagement, and responsiveness throughout the process. Regular email updates were used to follow up on data monitoring, inform stakeholders of upcoming appointments, and address data processing requests. Upon finalizing the intervention, participants had the opportunity to provide feedback, contributing to continuous improvement. Additionally, a monthly newsletter was established to keep stakeholders informed about project developments, key findings, and upcoming initiatives, fostering ongoing dialogue and engagement within the cycling community.

Biological samples collection

At the end of their data collection, participants provided fasting venous blood (16 mL) and spot urine (~50 mL) samples. A trained nurse performed the blood draw following standard clinical procedures. Samples were transported under cooled conditions (2–8 °C) to the clinical laboratory within 2–4 h, where they were aliquoted for specific analyses. Hemogram and blood lipid profiles (cholesterol and triglycerides) were measured immediately upon arrival. All aliquots of blood and urine were subsequently stored at –80 °C for long-term preservation. The study protocol was approved by the National Ethics Committee of the Republic of Slovenia (Approval No. 0120–323/2023/6), and written informed consent was obtained from all participants.

Action phase: Uptake of results

The action phase will focus on collaborative efforts to mitigate bike users' exposure to air and noise pollution. Workshops will be conducted to review key findings (e.g., air and noise pollution hotspots), develop a comprehensive cycling map that consolidates alternative route options, and propose education campaigns to raise environmental awareness among cyclists. These initiatives will be based on cyclists' local knowledge of low-exposure and pleasant routes, which can be disseminated to improve biking experiences and infrastructure.

Environmental exposure assessment

Exposure to particulate matter

Personal exposure to particulate matter (PM) was assessed by i) evaluating PM values for each minute and ii) estimating the individual PM inhalation adjusted dose per recorded cycling route. The dose was calculated using PM concentration data from the Atmotube monitor, and participant characteristics (age, height, gender, and weight) recorded on their Route Comparator account.

Particulate Matter Monitoring. At the individual level, PM concentration was measured using the Atmotube Pro, a compact personal monitor (86 mm × 50 mm × 22 mm, 105 g) that provides real-time monitoring of PM_1, $PM_{2.5}$, and PM_{10} [21]. The device was securely attached to participants' clothing, backpack straps, or bicycle handlebars to ensure consistent exposure measurement. PM concentrations were recorded at one-minute intervals (μg/m^3) and logged via the Atmotube mobile app, which also captured temperature, humidity, and atmospheric pressure.

Data collection covered various urban routes under different environmental and traffic conditions. Location tracking was used to correlate PM levels with specific locations.

Heart Rate Monitoring. To monitor participants' physiological responses to air pollution and noise exposure, we selected the Fitbit Charge 6 for continuous heart rate (HR) tracking.

Fitbit devices estimate HR using photoplethysmography (PPG)—a technique that detects blood volume changes in the microvasculature via light-emitting diodes and photodetectors. Each pulsatile change corresponds to a heartbeat and can be interpreted as an R wave [26]. This non-invasive, wrist-based method enables continuous and unobtrusive tracking of cardiovascular dynamics during physical activity.

Participants wore the device during all cycling activities, allowing for continuous HR measurements at one-minute intervals. This enabled us to capture resting, average, and peak heart rate values, as well as assess HR variability during rides. To maintain data quality, participants were instructed to wear the device snugly on the wrist and avoid adjusting it mid-ride.

Access to raw minute-level heart rate data required an application to Fitbit's Web API for Research. This process involved submission of a detailed data use proposal, documentation of ethics committee approval, and a description of the informed consent process. Despite receiving approval, each participant was still required to log into Fitbit's online platform individually to authorize data sharing and specify which data types they agreed to share. While this additional step enhanced user data protection, it introduced procedural challenges for researchers, which we address further in the Discussion section.

Inhalation Rate and Dose Calculation. The inhalation rate was estimated using the recorded average heart rate, along with participant age, gender, and height. Using this calculated inhalation rate and recorded $PM_{2.5}$ concentration, an inhalation-adjusted exposure rate (intake dose) was determined. The dose per kilogram of body mass was then calculated based on participant weight [27].

Exposure to noise

Environmental noise exposure was assessed using the NoiseCapture mobile application, an open-source Android tool designed for participative environmental noise mapping in real time [28]. NoiseCapture was initially developed as part of a participative approach to support community-driven environmental noise assessment [29]. Beyond its original goal, the app has since been adopted in a wide range of contexts: by individual users for personal monitoring, by advocacy groups working on noise pollution, in educational settings, by researchers for scientific studies, and by local authorities to inform noise-related urban planning [30].

Participants used the Dayton Audio iMM-6 Measurement Microphone. An extension cable positioned the external microphone for optimal exposure to ambient sound, with participants instructed to wear it on their helmet or backpack, facing backward.

The NoiseCapture app recorded A-weighted decibels (dB(A)) at one-second intervals, capturing equivalent continuous sound level (LAeq,1 s), maximum (Lmax), and minimum (Lmin) noise levels. Built-in GPS tracking enabled geospatial mapping of noise exposure along the cycling routes. Data underwent post-processing to remove anomalies and assess spatial and temporal variations in noise levels.

Participants were instructed to start and stop the recording manually at the beginning and end of each cycling commute.

Exposure to selected chemicals and potential biological effects

For the assessment of cyclists' exposure to urban environmental pollutants, selected chemicals (e.g., metals and polycyclic aromatic hydrocarbons, PAHs) will be measured in biological samples collected at the end of the study. To evaluate potential biological effects of air pollution and noise exposure, markers of oxidative stress and systemic inflammation will be analyzed in blood and urine samples. Biochemical analyses will focus on key biomarkers reflecting short-term physiological changes, including oxidative stress (activities of antioxidative enzymes, DNA damage [8-OHdG], and lipid peroxidation [8-isoprostane]) and inflammation (C-reactive protein, cytokines such as interleukins, and tumor necrosis factor-α). These biomarkers of effects will be used to compare physiological responses to varying exposure levels, as estimated through personal sensor data and/or chemical analyses of biological samples. The results will inform the evaluation of short-term biological impacts associated with environmental exposures during cycling and enable comparisons between groups of cyclists stratified by pollution levels along their daily routes. Although the impacts assessed are short-term, they may serve as early indicators of potential long-term health effects.

Bike commuting individual-level behaviour

To characterize the sociodemographic profile of participants and assess bike commuting behaviour, a structured survey was administered at the end of data collection using the EUSurvey online platform. The survey collected information on sociodemographic characteristics (e.g., age, gender, education, household income), general health status (e.g., chronic conditions, allergies), and various aspects of bike commuting, including frequency, motivations, perceived barriers, and use of alternative modes of transport. These questions were designed to contextualize participants' mobility patterns and identify key factors influencing their choice to commute by bike.

In addition, the survey included a section on environmental health literacy, adapted from Ciarloni [31], which assessed participants' awareness of air and noise pollution, their perception of related health risks, and their ability to access and act upon environmental data. This component was included to establish baseline data on bike users' understanding of their exposure to environmental pollutants during cycling and behavioural intention to reduce exposure (e.g., change route, avoid spatial-temporal hotspots, wear filters).

Route choice ethnographic assessment

This study used ethnographic methods to address the lived experience of bike commuters in the Urban Cycling Lab. Ethnographic research allows producing and understanding data within social contexts. It is increasingly used to make process evaluations of complex health-behaviour interventions and examine how the interventions operate to produce outcomes [32]. Our ethnographic approach included mobile interviews to document the psychosocial factors shaping bike commuters' route choice, perceived environmental exposure, opportunities to reduce exposure and potential impact of the citizen science intervention on these.

We conducted mobile "ride-along" semi-structured interviews with a subsample of bike commuters who volunteered to share their experiences in identifying routes with reduced exposure to environmental stressors. The topics covered during the interview included motivation for bike commuting and route choice, experience in the UKLL using digital tools for environmental assessment, environmental exposure awareness, experience using conventional and alternative routes, urban features enabling and hindering a positive bike commuting experience, perceived environmental stressors affecting bike commuting, perceived urban mobility challenges and improvement opportunities related to bike commuting.

Appointments were set to meet participants at their workplace at their usual departure time, and researchers rode along on their way home. Commuters were equipped with microphones to record the interviews and encouraged to provide real-time examples of their insights along the route.

Transcripts from the mobile interviews were systematically coded and analysed using a grounded theory approach, guided by the "practice theory" framework from the URBANOME project. Practice theory offers insights into social change through three elements: Meanings, Competencies, and Materials. This aligns with the COM-B model (Capability, Opportunity, Motivation), which shaped the Urban Cycling Lab intervention. The final analytic categories were bike commuters' route choice (Motivation/Meanings), perceived environmental exposure (Capability/Competencies), and strategies to promote low-exposure routes (Opportunity/Materials).

Data quality control

Multiple layers of data quality control were implemented to ensure the reliability of the collected environmental exposure data. To select an appropriate air quality sensor, an extensive review of available devices was conducted, leading to the choice of the Atmotube, which has a proven track record in research applications [22].

The Atmotube incorporates the Sensirion SPS30 PM sensor, independently validated and certified under the MCERTS Performance Standards for Indicative Ambient Particulate Monitors [23,24], ensuring compliance with stringent performance criteria for indicative air quality monitoring. Additionally, Atmotube holds RESET Grade B accreditation, further supporting its reliability. Post-processing techniques were applied to filter anomalies caused by sudden environmental changes or sensor drift [25].

Fitbit devices (Charge 4 and 5) were selected based on their demonstrated reliability in both clinical and real-world research settings. These devices have shown good agreement with clinical-grade ECG or chest strap monitors across a range of activities [33–36], supporting their use for ecological heart rate monitoring under mobile conditions.

Data integrity was further supported by internal database constraints, such as enforcing valid foreign key links between recording points and sessions. Selected data points were also visualized on the Route Exposure Compartor web app to facilitate anomaly detection, allowing both researchers and participants to identify and report irregularities, thereby enhancing transparency and trust in the data.

A custom script automated the import of data from Atmotube, NoiseCapture, and Fitbit into a PostgreSQL database. This script merged recordings, discarded entries shorter than two minutes or missing PM values, and pinged a healthchecks.io server at regular intervals (every 10–20 min, depending on the source) to monitor data flow. Alerts were triggered in the event of disruptions.

Location data quality was ensured by using GPS data from the NoiseCapture app rather than the Atmotube, due to its higher spatial accuracy. Sound measurements were calibrated before each deployment using a VOLTCRAFT SLC-100 Sound Level Calibrator, aligning the NoiseCapture app readings with the calibrator's reference values. Dayton Audio iMM-6 microphones, previously evaluated by Kardous and Shaw [37] were also used in these calibrations.

Although the Atmotube devices came pre-calibrated, an additional validation of PM measurements was conducted in real-world conditions. Atmotube data collected outdoors in the vicinity of fixed monitoring stations operated by ARSO (Agencija RS za okolje, Slovenian Environment Agency) in Ljubljana were compared against the corresponding station measurements. This approach ensured that sensor validation accounted for both spatial proximity and local environmental conditions [38,39].

Protocol validation

The Urban Cycling Lab is a transdisciplinary study and citizen science intervention within the URBANOME project. Using the array of methodologies described in this paper, this study comprehensively assesses bike commuters' exposure to environmental stressors at the individual level —particulate matter and noise—by integrating real-time geocoded environmental and physiological data collected through citizen science sensor-enhanced ICT infrastructure. This methodological approach ensures both high-resolution data acquisition and public engagement, providing an opportunity to understand and reduce exposure in urban microenvironments while empowering citizens as active participants in scientific research.

Previous studies examining bike users' exposure to multiple environmental stressors have employed a wide range of methodologies. These include the use of data from local bike-sharing systems, air quality indices, Green View metrics, and noise indices [2,40]; the application of geospatial and sensing technologies [3,41]; and participatory approaches involving bike users in data collection through biometric sensors and photovoice [42,43]; air pollution and noise sensor-based data and interviews [44]. To the best of our knowledge, this is the first study to assess individual-level exposure to particulate matter and noise by integrating bike users' actual mobility patterns, including their timing, location, and route preferences. While previous participatory studies have shown that engaging bike users in the evaluation of environmental stressors can enhance awareness and threat appraisal [31,44], they have also highlighted a common challenge: a perceived sense of helplessness in reducing exposure risks which may ultimately lead to inaction [45,46]. The UKLL study enables bike users to visualize their exposure levels on a web-based platform and supports them in finding opportunities to choose low exposure routes.

Our design serves dual purposes. First, by equipping bike commuters with personal monitoring devices, we can quantitatively assess their exposure to environmental stressors in real-time. The combination of sensor data—measuring noise levels, air quality (particulate matter), and physiological responses—allows for the calculation of personal dose intake per cycled route. The geolocation of the data enables a wide range of analyses. The inclusion of (bio)chemical analysis of biological specimens (urine and blood samples) provides an additional layer of biological validation, assessing biomarkers of biological response, such as oxidative stress. This integration of environmental exposure and biological impact represents a robust methodological approach to understanding health risks for cyclists. Additionally, the ICT infrastructure offers a scalable, interoperable system for collecting, harmonizing, visualizing, and analysing citizen-generated data, combining researcher oversight with participant autonomy.

Second, the study applied a citizen science and behaviour change approach to promote the understanding of environmental exposure and environmentally aware route choice. Drawing on the COM-B model, the intervention was designed to support increased awareness of environmental stressors through self-monitoring and digital feedback tools, potentially influencing commuters' route decisions. These tools were designed to enhance capability (knowledge and self-monitoring skills), opportunity (identifying feasible, lower-exposure routes), and motivation (to regularly choose healthier routes).

The Urban Cycling Lab was situated within an Urban Living Lab (ULL) framework, which served not only as a setting but also as a methodological backbone of the intervention. The ULL enabled multi-stakeholder collaboration, real-world experimentation, and iterative co-creation of tools and strategies. Stakeholder collaboration was a fundamental component of the study, ensuring both effective recruitment and practical application of findings. The multi-sectoral network facilitated outreach through word-of-mouth, snowball referrals, and established communication channels with grassroots cycling networks. A particularly effective strategy was partnering with an urban cycling-focused NGO, which actively promoted the project and significantly improved recruitment. Based on this experience, we recommend that future ULL projects formally include topic-specific NGOs as project partners whenever feasible. This underscores a key added value of the citizen science approach: it not only informs individual behaviour change but also creates a feedback loop for advocacy, policy and planning, by elevating citizens' perspectives into urban governance.

Limitations

Despite a carefully designed methodology, several practical challenges emerged during implementation. These can be grouped into three main categories:

1. Device-Related Challenges

- **Microphones**: Calibrated AUX-connected microphones were chosen over Bluetooth alternatives to ensure higher data quality. Over time, wear and tear caused AUX extension cables to peel and some microphones to fail. Backup components were maintained to mitigate these issues.
- **Fitbit devices**: Initial enrolment sessions were conducted in groups, during which participants were trained to use the devices. This caused connectivity problems when multiple devices were in close proximity. Switching to individual enrolment appointments, where participants set up and trained on devices one at a time, improved pairing reliability and data syncing.
- **Atmotube sensors**: Early GPS readings were low-quality, limiting exposure tracking during commutes. Collaboration with the developers enabled a "high-precision GPS" mode. The default air quality index, which aggregated PM and VOC readings, sometimes caused confusion; participants were instructed to interpret PM and VOC values separately. Over time, some units failed, losing PM sensing or connectivity, and backup devices were used to ensure continuity.

2. Participant adherence to planned routes

The original study design included a control group maintaining a consistent commuting route and an intervention group alternating between a “conventional” (main streets, bike lanes) and an “alternative” (quieter secondary streets) route to assess exposure differences. After three months of piloting, participants in the intervention group did not strictly follow the planned weekly pattern, often mixing routes or making minor modifications that did not result in meaningful exposure differences. The study design was therefore adapted to a flexible citizen science approach, allowing participants to choose routes according to their commuting habits and interests while still collecting valuable exposure data.

3. GDPR compliance and enrolment procedures

GDPR constraints prevented pre-configuring devices with participant data before obtaining consent. To address this, a stepwise enrolment process was implemented, where participants were registered, consented, and then guided through device setup and training in individual appointments. This ensured both compliance and reliable device configuration.

4. Transferability and lessons for sensor-based citizen science

These challenges highlight the importance of planning for redundancy, anticipating hardware degradation, and establishing robust workflows. Access to device APIs and mature digital tools facilitated automation, customization, and participant usability. The protocol’s core principles -citizen science sensor-based monitoring-, are broadly transferable to other cities, but adaptation may require consideration of digital literacy, local infrastructure and safety conditions. Population engagement strategies should account for varying levels of digital literacy; participants less familiar with digital tools may need additional support during enrolment and training. Factors such as bike lane availability, traffic density, road quality, accident risk, and crime rates may influence where and how participants can safely collect data. Environmental context, including pollution sources, noise hotspots, and green spaces, may necessitate tailored route planning. By anticipating these factors, other cities can implement participatory, evidence-informed interventions while maintaining data quality and participant safety.

Overall, despite these challenges, the Urban Cycling Lab outlines a replicable, transdisciplinary methodology for assessing environmental exposures among urban cyclists, providing a methodological model for similar citizen science interventions in diverse urban contexts.

CRediT author statement

María Rubio: Conceptualization, Visualization, Writing- Original draft preparation. **Rok Novak**: Conceptualization, Methodology, Writing- Reviewing and Editing. **Janja Snoj Tratnik**: Conceptualization, Methodology, Writing- Reviewing and Editing. **Davor Kontić**: Conceptualization. **Gregor Bučar**: Software. **David Kocman**: Conceptualization, Methodology, Validation, Supervision.

Supplementary material *and/or* additional information [Optional]

S1. ICT Infrastructure S2. Enrolment form
S3. Devices Protocol UKLL

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.mex.2025.103657.

Data availability

Data will be made available on request.

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