Environmental Research 226 (2023) 115685

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Review article

Integrated assessment of personal monitor applications for evaluating exposure to urban stressors: A scoping review

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ARTICLE INFO

Handling Editor: Jose L Domingo

Keywords:
Exposure
Urban
Environmental health stressors
Quadruple helix model
Citizen science

ABSTRACT

Urban stressors pose a health risk, and individual-level assessments provide necessary and fine-grained insight into exposure. An ever-increasing amount of research literature on individual-level exposure to urban stressors using data collected with personal monitors, has called for an integrated assessment approach to identify trends, gaps and needs, and provide recommendations for future research. To this end, a scoping review of the respective literature was performed, as part of the H2020 URBANOME project. Moreover, three specific aims were identified: (i) determine current state of research, (ii) analyse literature according with a waterfall methodological framework and identify gaps and needs, and (iii) provide recommendations for more integrated, inclusive and robust approaches. Knowledge and gaps were extracted based on a systematic approach, e.g., data extraction questionnaires, as well as through the expertise of the researchers performing the review. The findings were assessed through a waterfall methodology of delineating projects into four phases. Studies described in the papers vary in their scope, with most assessing exposure in a single macro domain, though a trend of moving towards multi-domain assessment is evident. Simultaneous measurements of multiple stressors are not common, and papers predominantly assess exposure to air pollution. As urban environments become more diverse, stakeholders from different groups are included in the study designs. Most frequently (per the quadruple helix model), civil society/NGO groups are involved, followed by government and policymakers, while business or private sector stakeholders are less frequently represented. Participants in general function as data collectors and are rarely involved in other phases of the research. While more active involvement is not necessary, more collaborative approaches show higher engagement and motivation of participants to alter their lifestyles based on the research results. The identified trends, gaps and needs can aid future exposure research and provide recommendations on addressing different urban communities and stakeholders.

1. Introduction

Poor air quality (hereafter AQ), noise, heatwaves and other environmental urban stressors are associated with 13% of deaths in the EU, air pollution being foremost among these with over 400 000 premature deaths, followed by 12 000 associated with environmental noise

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https://doi.org/10.1016/j.envres.2023.115685
Received 12 January 2023; Received in revised form 23 February 2023; Accepted 11 March 2023
Available online 13 March 2023

(European Environment Agency, 2021). In this review, the three environmental urban stressors primarily assessed are air pollution, noise and thermal burdens (causing stress). Dense urban areas are more likely to experience multiple challenges in terms of exposure to urban stressors, from increasing levels of traffic and therefore associated air and noise pollution (Liang and Gong, 2020; Zhang and Batterman, 2013), accommodating tourism and other services with residential use (Wetzstein, 2017), balancing space for efficient transportation and greenspace (Chen and Chang, 2015), developing systems and techniques to tackle the consequences of more frequent heatwaves (Hintz et al., 2018), etc.

Increased concentrations of air pollutants can have detrimental effects on human health, ranging from respiratory and cardiovascular diseases, neuropsychiatric complications, eye irritation, and skin diseases to long-term chronic diseases such as cancer (Ghorani-Azam et al., 2016; Manisalidis et al., 2020). Long-term exposure to particulate matter is related to cardiovascular diseases (Hamanaka and Mutlu, 2018), infant mortality (Manisalidis et al., 2020), and an increased risk of hospital admission for cardiovascular and respiratory diseases (Dominici et al., 2006).

Noise pollution can lead to several negative health effects, such as increased blood pressure and cardiovascular diseases (Münzel et al., 2017), higher levels of stress, and an increased risk for stroke (Münzel et al., 2020). Vulnerable groups, such as children, are more impacted by cognitive effects of noise, and evidence shows that noise exposure in schools can lead to reading and memory issues in children (Kamp and Davies, 2013; Stansfeld and Clark, 2015).

Extreme temperatures can lead to overheating, causing cardiopulmonary problems and increased cardiovascular mortality, disrupted sleep, impaired cognitive performance, and increased risk of suicide and hospital admission for mental illness (Khosla et al., 2021).

Urban stressors are interconnected. For example, due to higher temperatures, ozone levels can rise, increasing cardiorespiratory mortality and morbidity (Tong et al., 2021).

As research on exposure to urban stressors takes place in complex urban environments, it often involves multiple stakeholders and can provide opportunities for stakeholder-based initiatives (Soma et al., 2018). To provide a simplified and more manageable overview, the quadruple helix model is frequently applied (Bellandi et al., 2021). It presents an upgraded version of the triple helix model, as it includes civil society (Roman and Fellnhofer, 2022). The quadruple helix model thus divides stakeholders into four groups – academia and research, civil society and NGOs, businesses and the private sector, as well as government and policymakers (Arnkil et al., 2010). Such an approach provides several options to review the motivations and engagement of each group as well as their interactions.

Recent technological developments have enabled low-cost portable sensors to offer novel insight into exposure to urban stressors on a granular, individual level in multiple domains, which is not achievable with monitoring station networks. Though low-cost AQ sensors have often been subject to poor performance, erroneous data, and other issues, the narrative has been changing in the past few years as the devices become more reliable and accurate (Lewis and Edwards, 2016; Morawska et al., 2018; Giordano et al., 2021). These devices have been widely used in the past decade and provide researchers with affordable and highly customizable tools to collect the data needed for exposure assessment (Chatzitheochari et al., 2018; Leaffer et al., 2019). Their wearability, portability, and generally small size provide the opportunity to collect data in various domains or environments, e.g., indoor (Sá et al., 2022), outdoor (Chatzidiakou et al., 2019), traffic (Motlagh et al., 2021), and greenspace (Mueller et al., 2022). As smartphones have become ubiquitous, researchers often use them as low-cost sensors for noise measurements (Bocher et al., 2017), and they have been shown to provide accurate fit-for-purpose data (Aumond et al., 2017).

When participants use and host the devices that collect the data for exposure assessments and provide additional feedback, the approach begins to verge on citizen science (Oyola et al., 2022). Participants can become even more involved by co-creating research and collaborating in its dissemination. Depending on the level of participation, citizen science projects can be split into four levels: crowdsourcing, distributed intelligence, participative citizen science, and collaborative citizen science (Haklay et al., 2013). With participants becoming more involved and making significant contributions to research, issues of intellectual property and data privacy can emerge (Scassa and Chung, 2021).

The purpose of this scoping review was to identify good practices and concepts in low-cost sensor-based exposure to urban stressors research and to identify gaps (Munn et al., 2018). Therefore, three specific aims were identified for this review:

i) Determine the current state of exposure research, based on individual-level measurements using personal monitors (low-cost sensors and wearables), by using data extraction questionnaires and expertise of the researchers performing the review.
ii) Analyse research with a waterfall methodology, delineating projects into distinct phases. Using this data, gaps and needs will be identified for each specific phase and overall project/research design.
iii) Provide recommendations for developing more integrated, inclusive and robust approaches in utilizing personal monitors to aid exposure assessment, connecting stakeholders and engaging participants in urban areas.

A qualitative and quantitative review was conducted, with papers evaluated based on four general aspects: a) scope of exposure assessment, b) engagement of stakeholders, c) inclusion of citizen science principles, and d) consideration of ethical and intellectual property aspects. This review provides an overview of the current state of research in using personal monitoring devices for providing inputs for exposure assessment to urban stressors.

2. Materials and methods

This section explains the process in selecting the papers for this review, including the specific keywords. Exclusion criteria are listed in section 2.2, which were further employed to select the papers pertinent to the review topic. A PRISMA flowchart is added for a visual aid to the selection process. Section 2.3 describes data extraction, which was conducted with an online questionnaire. The queries were based on four general aspects: scope of exposure assessment, stakeholder engagement, involvement of participants, and ethical considerations.

2.1. Identification: Selection of papers

A review of currently available research on the topic of assessing individual-level exposure to urban stressors by using low-cost or next-generation sensors and monitors was conducted. Papers published between January 1, 2004 and August 17, 2021 and collected from Scopus (473) and Web of Science (308) were considered in the first round of reviews. The search queries, delimited by the "AND" Boolean in four building blocks, were as follows:

- observed urban stressors or measured parameters: ("particulate matter" OR "heart rate" OR "movement" OR "activity" OR "GPS" OR "gas*" OR "air*" OR "pollut*" OR "PM" OR "NO2" OR "CO") AND
- mode of data collection, focused on low-cost and wearable devices: ("exposure sens*" OR "mobile sensor node*" OR "low-cost sensor" OR "wrist-worn" OR "wearable sens*" OR "portable sens*" OR "sensor network" OR "crowd sensing" OR "participatory sensing") AND
- centred around exposure and urban health: ("exposome" OR "agent-based model" OR "intake dose" OR "exposure*" OR "urban health" OR "wellbeing" OR "liveability" OR "health concerns") AND
- an urban environment: ("urban*" OR "city" OR "municipality")

2.2. Screening: Titles, abstracts, and whole papers

After the initial title screening, 288 papers remained. Further title and abstract screenings were performed by two reviewers. The exclusion criteria were the following:

- no use of low-cost personal/individual-level or household sensors/devices or smartphones
- no mention of any urban environmental stressors: gaseous pollutants, e.g., NO_2, CO; particulate matter (hereafter PM) pollution – all sizes from ultrafine particles (hereafter UFP) to PM_{10} or dust; noise; temperature; in relation to green and blue spaces; activity/heart rate connection; etc.
- the study was not applied in an urban setting
- if the focus of the paper was only on occupational health exposures related to an industry sector e.g., agriculture, mining, or manufacturing, and so not in an urban setting
- the use of devices/methods applied only at specific high-exposure events, e.g., music festivals/concerts/dust storms
- description of a device, a design, calibration, etc., without any application, implementation, or use in an urban environment

This step yielded 100 papers. After text screening, an additional 8 review papers and 6 papers not relevant to the topic were removed. In the end, 86 were included in the review , and one paper, describing a specific use of data, was replaced by a paper describing the same project ("Sniffer Bike" (Wesseling et al., 2021)) in greater detail.

The identification of studies is summarized as a PRISMA flowchart (Fig. 1).

In addition to the outcomes resulting from the literature reviewed, several review papers on the topics of sensor technologies, measuring exposure and urban stressors, as well as citizen science and other participatory approaches were considered (see section 4).

2.3. Evaluation and data extraction

The best practices in using low-cost sensors and monitors for exposure assessments were considered. A quantitative and qualitative data extraction was performed using an online questionnaire (Appendix 1). Specific queries were extracted from four evaluation criteria:

- Scope of exposure assessment was reviewed, based on methodological approaches, including the number and type of devices used (Helbig et al., 2021), data collection and harmonization protocols, time–activity profiling, domains of interest (Leung, 2015; Khan et al., 2018) (outdoor, indoor, traffic, etc.), and the integration of external data sources, e.g., earth observation (hereafter EO), monitoring/weather stations. In addition, the involvement and number of participants and geographical and temporal extent were considered.

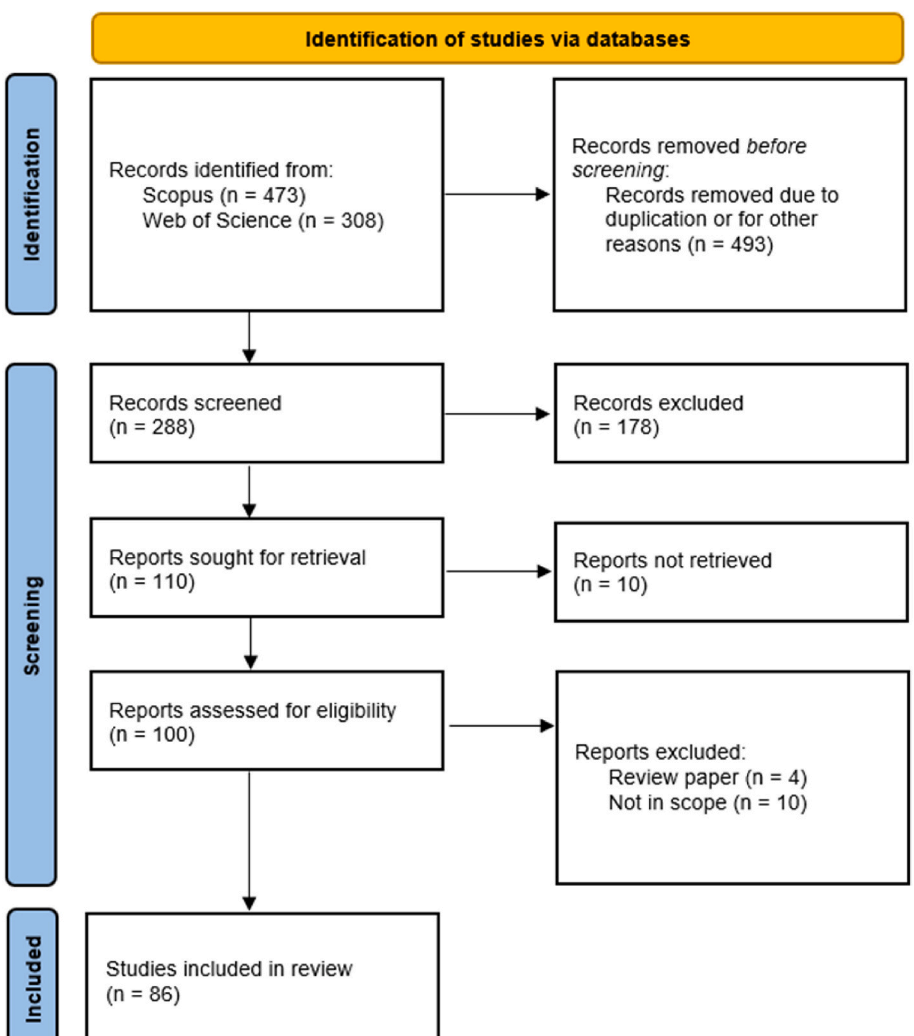

Fig. 1. PRISMA flowchart of paper identification, screening, and inclusion in review (Stansfeld and Clark, 2015).

- Stakeholder engagement was assessed based on the quadruple helix model of stakeholders (Arnkil et al., 2010): (i) academia/research, (ii) society/NGOs, (ii) businesses, and (iv) government/policy-makers. Each paper was assessed on the role and involvement of these groups.
- Involvement of participants was assessed according to four general levels (Haklay et al., 2013): (i) crowdsourcing, (ii) distributed intelligence, (iii) participative citizen science, and (iv) collaborative citizen science. Context on participant engagement and communication was included.
- Ethical considerations were evaluated based on the inclusion of ethics boards, data and privacy protection protocols, and intellectual property aspects (Resnik et al., 2015).

3. Results

This section is comprised of five subsections and details the results of the data extraction and review process. Initially, some general characteristics of the papers are provided, followed by subsection 3.2 exploring the results based on the first evaluation criteria – scope of exposure assessment. Several aspects are analysed, including the devices and methods used, number of participants included and their involvement, domains used in the assessment and data collection and stressors. Subsection 3.3 details the results on stakeholder engagement, based on the quadruple helix model, including the type of stakeholder(s) engaged, their involvement, and any tangible outcomes produced by the project. In subsection 3.4, the results of the review of citizen science and other participatory approaches are presented. These are separated based on four levels of participant inclusion, spanning from a crowdsourcing approach to collaborative citizen science. The last subsection, 3.5, shows different aspects of ethics, privacy, data protection, and intellectual property issues and challenges.

3.1. General characteristics and geographic distribution

Fig. 2 shows the number of included papers by the year the research was conducted (for those that provided this information) and the stressors they addressed, indicating a gradual year-to-year increase of respective studies.

Most of the reviewed studies were conducted in Europe, North America or Asia, as is evident in Fig. 3. This is a trend observed in other reviews and is a consequence of funding and prioritization for urban stressors in Europe and North America, as well as higher degrees of urbanization compared to other regions.

3.2. Scope of exposure assessment and applicability

Within the scope of applicability of exposure assessment approaches, the review focused on 1) the method used for exposure assessments, 2) participants in the study, 3) domains of interest, 4) stressors assessed per domain, 5) any activity data collection, and 6) ancillary data considered.

3.2.1. Method of exposure assessments

The exposure assessment method was determined by the number and type of devices used, by ancillary data (e.g., activity logs, AQ monitoring stations), and by addressed health outcomes.

All papers were evaluated based on the complexity of the exposure assessment and assigned to one of two categories:

- Targeted approach: in general, papers included in this category use a single low-cost device or system, which can include multiple sensors, and calculated exposure to various stressors. The approach can include using smartphones as data collecting devices.
- Extensive approach: employing multiple devices and monitors in combination with activity, microlocation, or other external data sources (e.g., earth observation, near real-time traffic data, AQ data) and measuring environmental and physiological/biometric parameters, such as heart rate, body temperature, movement, and/or others. This level of complexity can include estimates of the intake dose of various pollutants, complex movement-based exposure, etc.

More than half the papers were assigned to the category of targeted approach. The main stressor analysed was air pollution (predominantly PM) due to the severity of the negative effects it has on human health (Varaden et al., 2021; Mousavi and Wu, 2021; Wesseling et al., 2021; Chen et al., 2020; Agrawaal et al., 2020; Brzozowski et al., 2020), as a result of concerns voiced by participants through citizen science approaches (da Schio, 2020), or as a main source of air pollution, e.g., combustion of solid fuels or traffic (Johnston et al., 2019; Coffey et al., 2019). PM measurements were often accompanied with NO_2, CO, CO_2, VOC, and other pollutants (Tan and Smith, 2021; Frederickson et al., 2020; Hanoune et al., 2019; Dam et al., 2017; Valle et al., 2017; Ali et al., 2015; Sm et al., 2019) or with temperature and humidity measurements (Tan et al., 2020; ChewThornburgJackSmithYang, 2019; Boso et al., 2020). Noise was primarily assessed using smartphone apps, observing general and long-term trends (Ghosh et al., 2019; Lefevre and Issarny, 2018), singular events (Zipf et al., 2020), or comparing indoor and outdoor exposure near busy roadways (Leao et al., 2014).

In terms of tools employed to measure the (environmental) burden of urban stressors, the low-cost sensors used most frequently were portable and wearable. Portable PM, gaseous air pollutants, and noise measuring sensors were generally carried in either backpacks or suitcases (Varaden et al., 2021; Tan and Smith, 2021; Frederickson et al., 2020; Tan et al., 2020; Soares et al., 2020; Johnston et al., 2019; Ghosh et al., 2019; Lefevre and Issarny, 2018; Valle et al., 2017; Dalla Valle et al., 2017; Liu et al., 2015; Leao et al., 2014; Hofman et al., 2021; Liu et al., 2020).

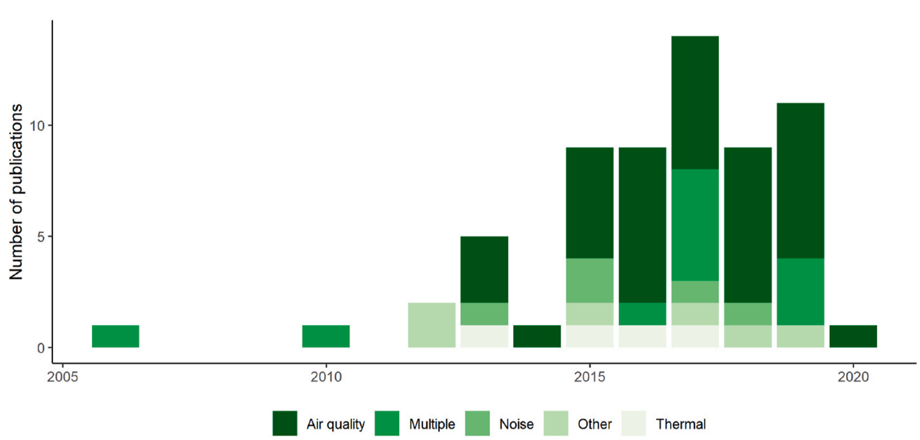

Fig. 2. Number of publications by year of publication and evaluated stressors.

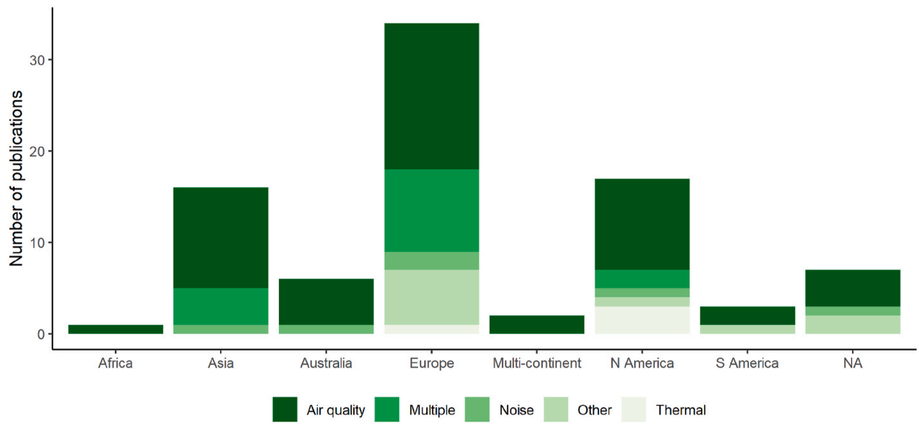

Fig. 3. Number of publications by region and evaluated stressors.

Although personal monitors are becoming smaller and more versatile, there remains the issue of incorporating ancillary components, which can bulk up the measuring equipment, making it less attractive for use. Fewer papers describe using wearable sensors, worn on a wrist, an arm, a belt, or on another part of the body/clothes (da Schio, 2020; Pigliautile et al., 2020; Chen et al., 2020; Zhang et al., 2019; Dam et al., 2017; Dons et al., 2017; Sugg et al., 2018; ChewThornburgJackSmithYang, 2019; Agrawaal et al., 2020; Puhakka et al., 2020). Those least used were stationary sensors (Perelló et al., 2021; Mousavi and Wu, 2021; Pigliautile et al., 2020; Coffey et al., 2019; Haynes et al., 2019; Alsina-Pagès et al., 2016; Uejio et al., 2016; Boso et al., 2020; Brzozowski et al., 2020) as they were not explicitly included in the search query for this review.

Smartphones have been shown to be convenient for use as portable measuring devices as they have multiple imbedded sensors and are used widely by urban populations. The integrated sensors (and modules that can be used as sensors) include a barometer, a gyroscope, an accelerometer, a camera, location/GPS tracking, and a microphone. As such, they can serve as a tool to collect data on movement or activity (location/GPS) and for assessing greenspace, urban nature/greenery, scenicness (Zhang et al., 2021; Juntti et al., 2021; Ferrara et al., 2018; Seresinhe et al., 2019), and exposure to sunlight (Guo et al., 2015). They are also utilized to log measured data or subjective opinions on AQ (Ueberham et al., 2019; Grossberndt et al., 2020).

Several papers include smartphones as noise measuring devices (Zipf et al., 2020; Ghosh et al., 2019; Lefevre and Issarny, 2018; Zhang et al., 2017; Leao et al., 2014); however, for more accurate noise measurements, an external microphone is often connected with the smartphone (Herranz-Pascual et al., 2019; Ueberham et al., 2019; Roe et al., 2020).

Papers assigned to extensive approach category include:

- data on the burden of urban stressors
- activity or microlocation logging, in combination with personal monitors or smartphones
- integrating physiological/biometric parameters, such as heart rate, forced vital capacity, and movement into the exposure assessment
- providing real-time insights of the results during data collection
- integrating collected data with external data sources

Stationary sensors were usually used in exposure assessments to determine outdoor AQ in the immediate vicinity of the participant's residence (Barkjohn et al., 2020; Sinaga et al., 2020), measure concentrations of PM in different rooms at once (Hegde et al., 2020), or provide indoor AQ measurements in classrooms (Sharma et al., 2017). AQ monitoring and meteorological stations can be used to provide background data (Dekoninck et al., 2015; MacKerron and Mourato, 2013) and how they relate to health outcomes (Bui et al., 2020) and to inform models based on personal monitors (Mead et al., 2013). An integrated approach can also include other sources of data inputs, e.g., consideration of social and discomfort factors (Schnell et al., 2012), emotional wellbeing in connection with AQ (Lal et al., 2020), and health databases (Pala et al., 2019).

Heart rate and movement/activity data (or their metabolic equivalents) can be recorded by wearable activity trackers, and the data can be used to estimate the inhalation rate or intake dose of a specific pollutant (Hu et al., 2014a); however, this can also be estimated using respiratory rates for specific age groups (deSouza et al., 2021). Activities like sleep, working indoors, eating, and general home activities will usually lead to a lower inhaled dose, while walking and working out will result in a higher inhaled dose (Hu et al., 2014a). Heart rate monitors can also be used to analyse whether urban green environments reduce stress in individuals (Roe et al., 2020) or how the positive effects of physical activity are negated by the negative effects of air pollution (Laeremans et al., 2018).

More than a third of the papers consider health outcomes to a certain degree, generally in relation to exposure to air pollutants. They often assess the influence of AQ on human health by using health questionnaires and personal AQ monitors (e.g., Zhang et al., 2017; Valle et al., 2017; Schnell et al., 2012; Sarmiento et al., 2020). Medical health assessments provide researchers with objective data and allow them to identify relations between AQ and (respiratory, cardiovascular, etc.) health (Laeremans et al., 2018). Several papers focus on respiratory health, more specifically on asthma in children (Perelló et al., 2021; Bui et al., 2020) and the wider population, in regard to how it relates to exposure to traffic (Dons et al., 2017).

Papers often seek connections between urban stressors and perceived psychological stress or discomfort (Ma et al., 2021; Marquart et al., 2021b; Zhang et al., 2014; Roe et al., 2020) and how inhabitants perceive their environments (Herranz-Pascual et al., 2019).

3.2.2. *Study participants*

For each of the reviewed papers, the number and characteristics of the study participants were extracted. The papers were categorized based on the number of participants they included. Most of the reviewed studies recruited less than 1000 participants. Given the fact that large population cohorts produce results with higher statistical significance, they offer a smaller level of complexity; therefore, the studies with >1000 participants were primarily assigned to the targeted approach category (refer to section 3.2.1). Most relied on smartphone apps and the data they generate, e.g., participants assessing their surroundings (Ferrara et al., 2018; Lefevre and Issarny, 2018; MacKerron and Mourato, 2013) or apps tracking their movement and activity (Fallah-Shorshani et al., 2018; Puhakka et al., 2020), or did not use personal monitors but instead deployed passive static NO_2 samplers (Perelló et al., 2021). One paper in the >1000 participants group presents results from a personal exposure campaign using low-cost wearable sensors, which was part of a larger cohort study (Arku et al., 2018). Approximately one-fourth of the papers did not specify the number of participants (Fig. 4).

In terms of the characteristics of the study participants, the majority of papers do not report any details about the groups of people recruited, or studies simply recruited participants based on their residence within the study area (Fig. 5).

Urban stressors can have the most detrimental effects on vulnerable groups, e.g., children or adolescents (Mahajan et al., 2021; Chen et al., 2020; Johnston et al., 2019; Fallah-Shorshani et al., 2018; Schnell et al., 2012) (and their families (Varaden et al., 2021; Perelló et al., 2021)), including children with asthma (Barkjohn et al., 2020; Bui et al., 2020), the elderly (Chatzidiakou et al., 2020; Roe et al., 2020), adults with self-reported common mental health problems (McEwan et al., 2020), people receiving emergency care (Uejio et al., 2016), and those with movement disabilities (Mora et al., 2017); therefore, these groups are represented in the studies to a large extent. Additionally, as research is predominantly conducted at universities and research institutes, it often relies on students, employees, and their families to be participants (Zhang et al., 2021; Marquart et al., 2021b; Zipf et al., 2020; Gelb and Apparicio, 2020; Liu et al., 2020; Hanoune et al., 2019; Mallires et al., 2019; Sharma et al., 2017; Sugg et al., 2018) or on the researchers conducting the study themselves (Tan and Smith, 2021, deSouza et al., 2021). Studies also involved participants based on specific conditions that could result in high exposure levels, frequently pertaining to appliances or devices (e.g., a wood-burning stove (Boso et al., 2020)), or a Purple Air device (Coffey et al., 2019) used to account for the possible impact on the AQ in their residence.

Smartphone and portable/wearable devices allow researchers to recruit participants that move around and cover large areas, e.g., cyclists (Wesseling et al., 2021; Ueberham et al., 2019; Dekoninck et al., 2015; Chew et al., 2019), drivers (Frederickson et al., 2020), or subway passengers (Zhang et al., 2017).

3.2.3. *Domains of interest*

Concerning the domains of interest, these were categorized as follows. Approximately half the papers cover only indoor spaces or in combination with outdoor spaces, as shown in Fig. 6. Recent studies have shifted their interest to the cumulative effect of outdoor and indoor pollution by adopting dynamic exposure models, as people spend most of their time indoors. Comfort and wellbeing in indoor spaces are correlated with higher productivity and better performance (Wyon, 2004). In the thermal stress domain, prototype devices were deployed in real-life environments to assess the thermal comfort of, for example, office workers, and simultaneously to offer options to reduce energy usage (Nanni et al., 2017), develop a system to measure asthma symptom triggers (Mallires et al., 2019), assess exposure to urban greenery (Zhang et al., 2021), or correlate indoor AQ in classrooms with occupancy rates (Hanoune et al., 2019; Sharma et al., 2017). The majority of the studies focused on the outdoor environment (or in combination with the indoor environment), while a minority specifically focused on green spaces.

3.2.4. *Main stressors addressed per domain*

Stressors addressed in each domain (as described in section 3.2.3) were analysed. The most frequent stressor addressed in almost all domains was air pollution, which was also the sole stressor measured in most cases. Thermal stressors were analysed within the indoor (Uejio et al., 2016) and outdoor (Ueberham et al., 2019; Sugg et al., 2018) domain or in indoor–outdoor combination (Fekih et al., 2021; Rebeiro-Hargrave et al., 2020; Hass and Ellis, 2019; Schnell et al., 2012). Noise was an important stressor in relation to the outdoor environment (Ghosh et al., 2019; Herranz-Pascual et al., 2019; Lefevre and Issarny, 2018) or transport domain (Marquart et al., 2021a; Zipf et al., 2020; Gelb and Apparicio, 2020; Ueberham et al., 2019; Dekoninck et al., 2015; Roe et al., 2020) and, to a lesser degree, within the indoor domain (Ma et al., 2020; Soares et al., 2020; Leao et al., 2014), although the latter were a part of campaigns that included the measurements of multiple environmental stressors. Within all the domains (apart from transport) other health stress parameters such as temperature, humidity, light, metabolic markers, mood/emotional markers, mobility patterns, and the presence greenspace were also included.

3.2.5. *Activity data collection*

Activity data can provide additional context to exposure assessments, and the technologies used, e.g., smartphone apps, questionnaires, and activity sensors, are also considered in this review. Most of the studies did not employ a technology for recording activity. For the ones that did, a smartphone app was the most common tool. Smartphone apps, used in outdoor domain-based papers, can prompt participants to identify their current activity (Seresinhe et al., 2019) or what they were doing in a past time interval, as determined by the users' movements (Lal et al., 2020), if they cycled to work (Chew et al., 2019), and why they took a specific cycling route (Ueberham et al., 2019). Studies involving the indoor domain are less reliable in terms of GPS, though there are options to use data from cell towers and Wi-Fi to improve location tracking (Glasgow et al., 2016). Another option is radio frequency identification which does not use energy and is less expensive and more transparent (Mora et al., 2017). Smartphones also collected activity data to accompany AQ data during specific activities (da Schio, 2020; Hu et al., 2014a) and employed gamification in assessments to provide context for medical conditions, e.g., asthma (Bui et al., 2020). Smartwatches and other wearable activity trackers were used to log data about activities predetermined on the device (da Schio, 2020; Hu et al., 2014a; Sugg et al., 2018; Puhakka et al., 2020), and several studies

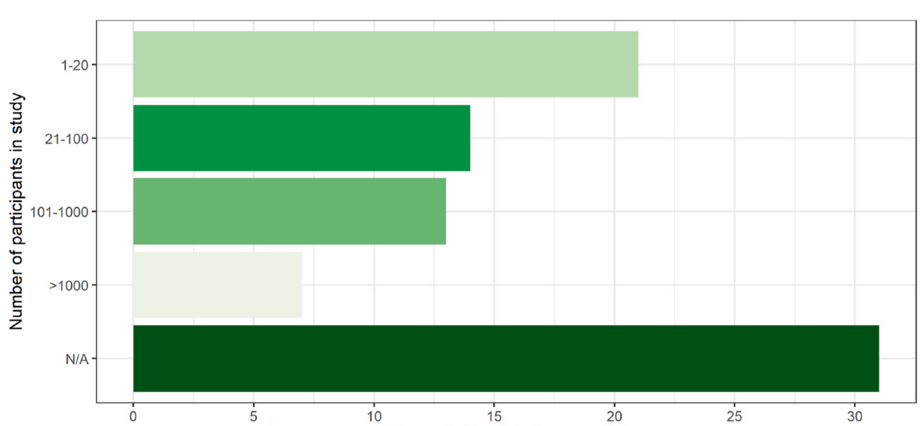

Fig. 4. Share of all papers based on categorization of the included studies according to the number of participants enrolled.

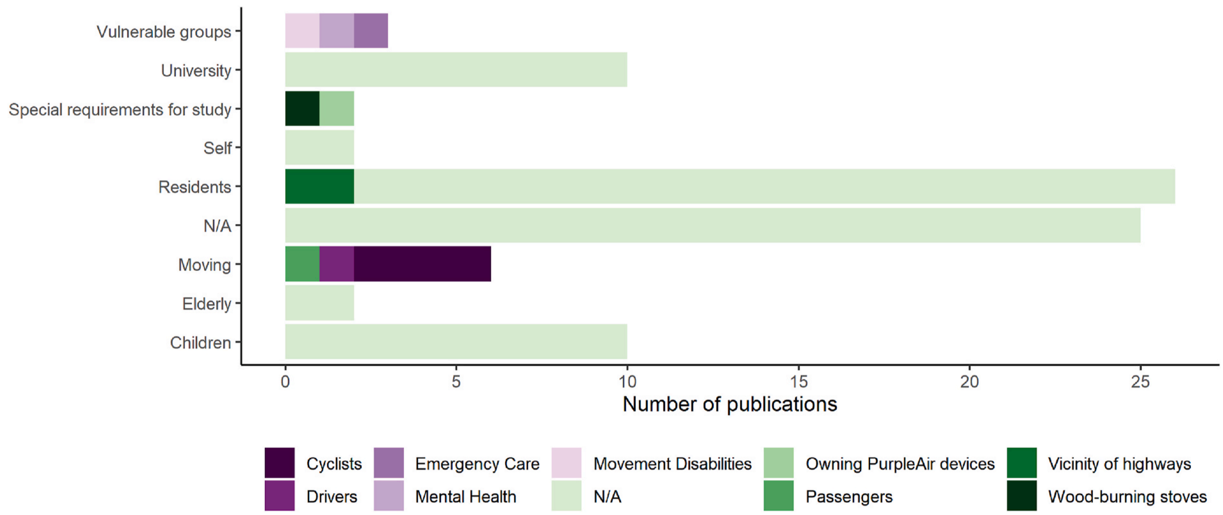

Fig. 5. Participant target groups as percentages of all considered papers and specific criteria required for inclusion.

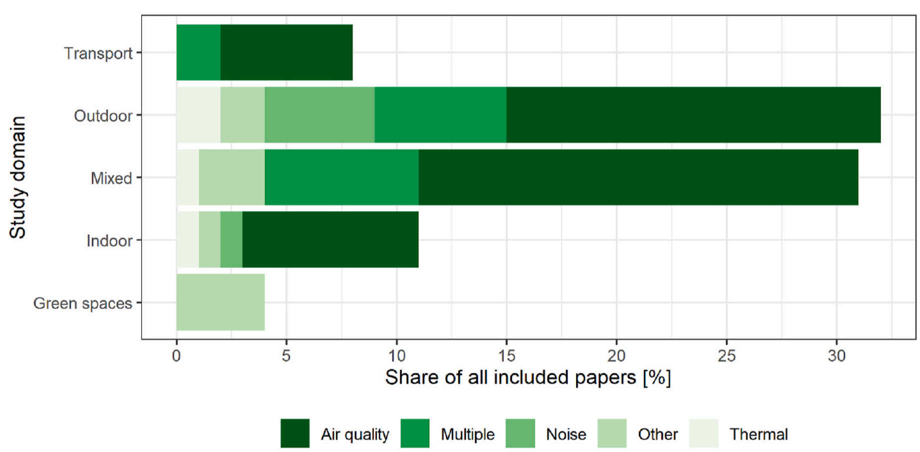

Fig. 6. Share of papers covering different domains and stressors. Categorization of the studies in the following domains: a) outdoors, b) combination of outdoor and indoor domains, c) indoors, d) transport, e) green spaces, and f) a combination.

included some kind of questionnaire or activity data diary in a digital/online format (Ma et al., 2020, 2021; Barkjohn et al., 2020; Sinaga et al., 2020; Hegde et al., 2020; Sarmiento et al., 2020).

3.2.6. Usage of external data sources

Exposure studies can include auxiliary data collected from various other sources to complement data from low-cost and wearable/portable devices. Land-cover and land-use data were used to determine green spaces in urban environments (Herranz-Pascual et al., 2019; Puhakka et al., 2020), whether these areas correlated with how participants observed and classified them (Seresinhe et al., 2019), and how built-up environments influenced exposure to urban heat stress (Sugg et al., 2018). Frequently, studies used near-by environmental and AQ monitoring stations to validate/calibrate devices, platforms, or models (Mousavi and Wu, 2021, deSouza et al., 2021; Wesseling et al., 2021; Fekih et al., 2021; Chen et al., 2020; Hass and Ellis, 2019; Hu et al., 2016) and to compare with results obtained from portable low-cost devices deployed in the field (Chatzidiakou et al., 2020; Mead et al., 2013). Data from AQ monitoring stations and EO were used in combination with location data, with overlaid GPS tracks to aid participant exposure assessment (Rebeiro-Hargrave et al., 2020), or with data on how participants perceived AQ in their environment (Grossberndt et al., 2020). Using EO and meteorological data can provide context for health and medical assessments and for determining environmental asthma triggers (Uejio et al., 2016; Bui et al., 2020) and the influence of environmental factors on the frequency of emergency calls.

3.3. Stakeholder inclusion

3.3.1. Types of stakeholders and their interaction

This section deals with the involvement of various types of stakeholders in the papers. Following the quadruple helix model (Schütz et al., 2019), which describes university–industry–government–public–environment interactions within a knowledge economy, the four general stakeholder groups are considered:

- *Academia/Research*: institutions of higher education and research
- *Government/Policymakers*: system or group of people governing an organized community, including those responsible for or involved in formulating policies
- *Society/NGOs*: various groups of individuals not professionally involved in research activities, including non-governmental organizations
- *Businesses*: entities engaged in commercial activities

The number of papers with various combinations of stakeholders involved, as well as respective topics addressed, is shown in Fig. 7. Involvement of stakeholders from academia and research dominated,

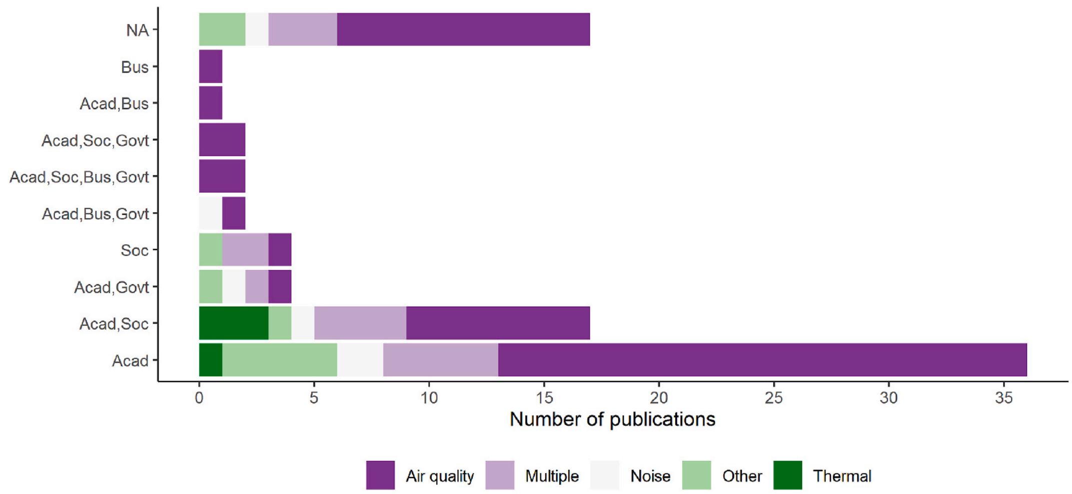

Fig. 7. Number of studies and their topics per combination of stakeholders involved and evaluated stressors. The quadruple helix stakeholders are abbreviated as Bus for business and private sector, Acad for academic and research, Soc for civil society and NGOs, and Govt for government and policymakers.

followed by society and NGOs, while governmental inclusion as well as that from the business sector were rare. In most cases, studies seemed strictly research-oriented. In case more than one stakeholder type was involved, this was related to the inclusion of non-professionals, either organized in groups, including NGOs, or individuals. In the society/NGO group, the multiple domain approach stood out.

3.3.2. Inclusion levels

The role of individual stakeholder inclusion was further analysed, considering the following possible options with increasing levels of inclusion:

- Stage 1: inclusion in the initial research design phase and/or provision of research findings
- Stage 2: in addition to first stage, inclusion in the data collection phase
- Stage 3: in addition to the first two phases, inclusion in data analyses and/or the communication/dissemination phase

Else, their role was limited to the recruitment of participants, financing, outside consultant, or another role.

The above-mentioned roles reported in the papers are summarized in Fig. 8 according to type of stakeholder group. With rare exceptions, research stakeholders were involved in all research phases. NGOs and similar stakeholders usually participated in the volunteer recruitment

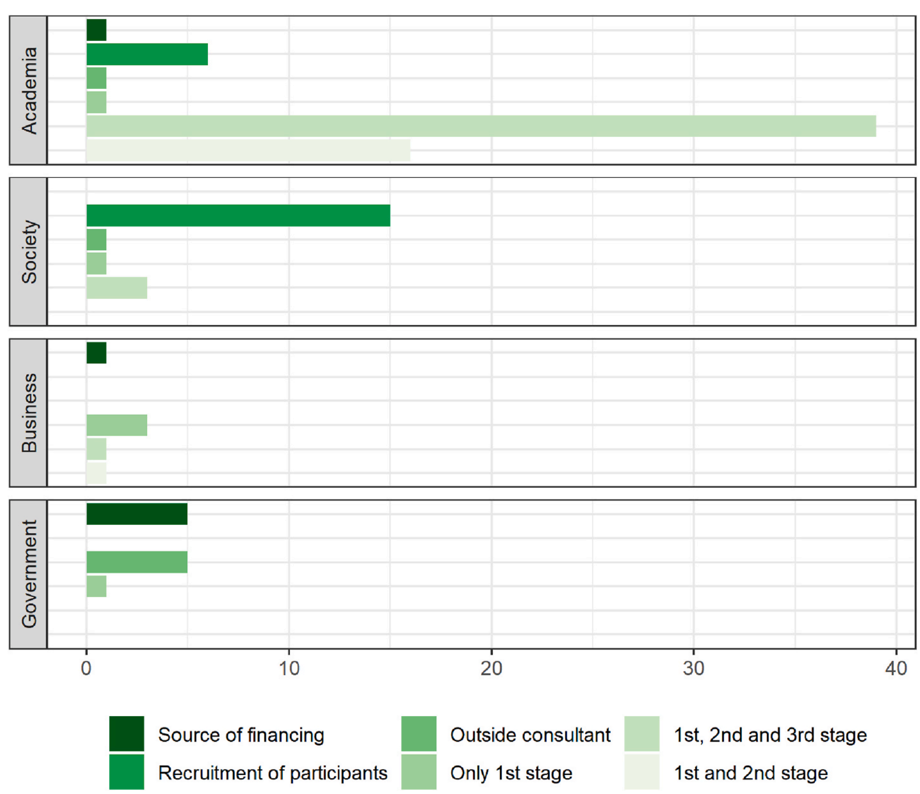

Fig. 8. Number of studies according to stakeholder group and type of involvement.

phase. Such examples were studies dealing with various approaches for individual-level exposure assessment and collaborating either in conducting measurement or in the testing of sensing technologies (Coffey et al., 2019; Herranz-Pascual et al., 2019; Ueberham et al., 2019; Pala et al., 2019; Glasgow et al., 2016; Mead et al., 2013; Sugg et al., 2018; Chew et al., 2019; Bui et al., 2020; Roe et al., 2020; Puhakka et al., 2020). On the other hand, governmental institutions usually participated as a funder or as an external consultant (Varaden et al., 2021; Perelló et al., 2021; Laurino et al., 2021; Mahajan et al., 2021; Gelb and Apparicio, 2020; Leao et al., 2014; Sarmiento et al., 2020). Where this was the case, the provision of meaningful information (i.e., on exposure) to policymakers and authorities was one of the main drivers and applications (Mahajan et al., 2021; Leao et al., 2014; Sarmiento et al., 2020). Similarly, the private sector functioned as financier and provider of equipment/infrastructure and other means for conducting the measurements. Some specific examples thereof comprise of company involvement in the design of the monitoring backpacks on loan and free of charge (Varaden et al., 2021), provision of an open data portal (Mousavi and Wu, 2021), and app development (Arku et al., 2018).

The motives for the involvement of different stakeholders varied. In the case of stakeholders from research and academia, their motivation was usually straightforward and comprised the generation of new scientific knowledge regarding exposure to urban stressors in various contexts, improvements in modelling tools to obtain finer spatio-temporal insights in respective exposures, or similar developments in other tools to be used as part of exposure assessment. Also, their motivation was to empower vulnerable populations and influence decision-makers. In the case of the general public and NGOs, motivation was driven by their desire to take part and contribute in new knowledge generation, direct improvements in specific living environments (Varaden et al., 2021; Roe et al., 2020; Sarmiento et al., 2020), but also involvement in the co-design and co-creation of the research process (Perelló et al., 2021; da Schio, 2020). In the case of governmental institutions, most were included in order to obtain support for their decision-making processes and access to concrete products and solutions that might improve overall quality of life in the city (e.g., Perelló et al., 2021; Mahajan et al., 2021; Lefevre and Issarny, 2018; Sarmiento et al., 2020; Hofman et al., 2021). In the case of stakeholders from business circles, their motivation stems all the way from altruistic cases of research support (Varaden et al., 2021; Mousavi and Wu, 2021; Mahajan et al., 2021) to interest in the innovative aspects of the tools developed and new business opportunities (Lefevre and Issarny, 2018; Hofman et al., 2021).

3.3.3. *Tangible outcomes or products*

Overall, more than a third of the papers report a tangible outcome or product resulting from the study. Of these, half are related to developing or deploying various monitoring systems (Fekih et al., 2021; Rebeiro-Hargrave et al., 2020; Soares et al., 2020; Hanoune et al., 2019; Mallires et al., 2019; Coffey et al., 2019; Haynes et al., 2019; Mora et al., 2017; Dam et al., 2017; Zhang et al., 2017; Arvind et al., 2016; Ali et al., 2015; Hu et al., 2014a; Bui et al., 2020; Agrawaal et al., 2020), followed by smartphone applications (Ferrara et al., 2018; Fallah-Shorshani et al., 2018; Lefevre and Issarny, 2018; Glasgow et al., 2016; Guo et al., 2015; Hu et al., 2014a; Leao et al., 2014; Hu et al., 2014b) and environmental models (Perelló et al., 2021; Mahajan et al., 2021; Chatzidiakou et al., 2020; Zipf et al., 2020; Dekoninck et al., 2015; Chew et al., 2019; Hofman et al., 2021). In two cases, pollution reduction is also identified as a tangible outcome (Barkjohn et al., 2020; Soares et al., 2020) (Fig. 9).

Outcomes in the form of monitoring systems comprised specific sensing devices, methodological frameworks, as well as tools for real-time data collection and interaction with subjects. Models dealt mostly with AQ issues, taking advantage of new sensing technologies to improve their resolution (Perelló et al., 2021; Chatzidiakou et al., 2020; Hofman et al., 2021), with one example of a holistic framework that embedded the social dimension in a technology-centric AQ sensing system (Mahajan et al., 2021). Models for exposure assessment as decision-support tools for policy makers were also present (Chatzidiakou et al., 2020; Dekoninck et al., 2015).

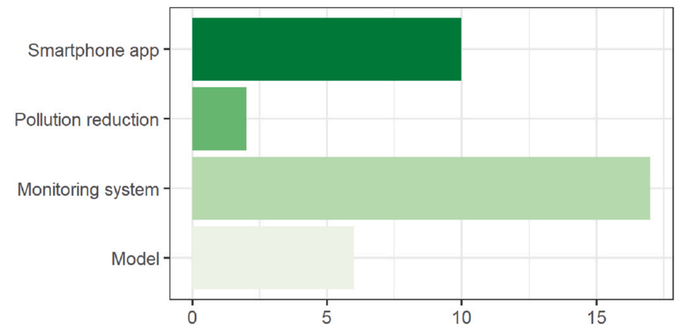

Fig. 9. Number of papers base on general categories of tangible outcomes or products.

3.4. *Citizen science and other participatory approaches*

Public participation in scientific research an take various forms (Shirk et al., 2012). In this section the level of participation is reviewed, that is, to what extent they were involved and how the data they collected were communicated back to them. Papers were classified according to four levels of involvement (Haklay et al., 2013):

- level 1 – crowdsourcing: people generated information passively, e.g., were invited to wear a sensor or have a sensor placed in their household/workplace (returned to the organizers)
- level 2 – distributed intelligence: people received some kind of training, provided information through observations, or interpreted existing information, e.g., by validating observations made by others
- level 3 – participative citizen science: the community defined the problem; it may be derived from previous projects (previous levels), thinking up new questions, etc.
- level 4 – collaborative citizen science: people participate at all levels, thinking up new questions, (co)designing the methods for data collection, and analysis

The urban stressors studied are variably present in different levels of engagement. AQ prevailed in all levels of involvement. However, noise measurements stood out for level 2, where participants provided their observations. Thermal stressors were studied only at level 1, where data were collected passively from participants. (see Fig. 10)

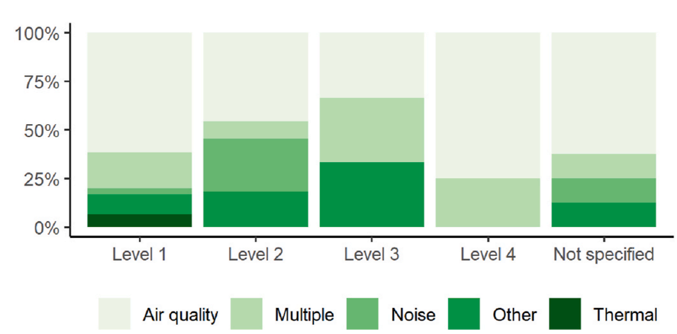

Fig. 10. Urban stressors and level of participant engagement in the reviewed papers.

For several papers, the level of participant involvement was not classified. In these cases, the papers do not provide any specific information on participant involvement and are more focused on technical development of the monitoring/sampling system.

3.4.1. Crowdsourcing

The majority of the papers were classified as level 1 – crowdsourcing, where participants carried a portable sensor unit on them or on their bike or vehicle or hosted them passively at their home, school, or workplace. Generally, these studies did not include information about feedback to the participants during or after the measuring campaign. In certain cases where participants used smartphone apps, they were shown real-time AQ data and visualizations (Rebeiro-Hargrave et al., 2020; Ghosh et al., 2019; Zhang et al., 2019; Guo et al., 2015; Leao et al., 2014; Seresinhe et al., 2019), though it was not necessary that the participants be in direct contact with the researchers (Mousavi and Wu, 2021). When participants received results after data collection had ended, it was in the form of a log in the app they used (Glasgow et al., 2016) or a comprehensive report with all the data they collected, with context from other participants, plots and other visualization, explanations, and recommendations (Rebeiro-Hargrave et al., 2020; Zhang et al., 2017). Involving participants more, e.g., by showing them real-time data on noise pollution with input options and providing comprehensive reports, showed that almost half of them were planning to use their smartphone to measure noise in the future (Zipf et al., 2020).

3.4.2. Distributed intelligence

In papers labelled level 2 – distributed intelligence, participants were more involved, going beyond hosting a device or inputting data on a smartphone. In some cases, participants hosted an AQ device but were more actively engaged, e.g., by providing objective measurements or participating in focus group discussion (Sinaga et al., 2020; Ueberham et al., 2019; Boso et al., 2020). A large proportion of papers report that the participants could see real-time data, and in two-thirds the participants actively inputted the data. About a third of the papers do not discuss reporting data to the participants, and two-thirds report that the participants did not see data after the measurement campaigns. Studies employed different ways to engage the participants, for example by allowing them more freedom in adjusting settings in the app they were using (Glasgow et al., 2016), allowing them to keep the app (Lefevre and Issarny, 2018), or having them actively input data on how they perceived green spaces (McEwan et al., 2020), the urban soundscape (Herranz-Pascual et al., 2019), or their exposure to various urban stressors (Ueberham et al., 2019). Using personal monitors was combined with multi-choice questionnaires, time–activity diaries (Mazaheri et al., 2018), or a web-based game to monitor perceived levels of pollution (Sîrbu et al., 2015). In Juntti et al. (2021), urban environmental quality and wellbeing were studied where participants took pictures with a smartphone app and were subsequently interviewed. On the other hand, Boso et al. (2020) employed a strategy where half the time the participants did not see any data and half the time they received instant feedback on indoor AQ; the authors showed that when participants were more engaged (had access to air pollution values), they had higher motivation and greater confidence in the information they had on their environment.

3.4.3. Participative citizen science

Papers classified as participative citizen science (level 3) also involved actively inputting data or hosting/wearing a device but included further involvement. Sarmiento et al. (2020) employed a citizen science model. In addition to wearable activity trackers and portable low-cost AQ sensor devices, a mobile app enabled residents to document neighbourhood features through geo-coded photographs, audio narratives, and GPS-tracked walking routes. Meetings were also conducted with the participants, one for each intervention and control area.

3.4.4. Collaborative citizen science

Four papers were assigned to collaborative citizen science (level 4), which, in addition to their actively inputting data, involved the participants in the design of aspects of the project. A key difference with previous levels is that in some cases the participants were involved in designing research questions and study protocols (da Schio, 2020). They received a comprehensive report and the final products of the data they collected and were offered a platform to connect with policymakers (Perelló et al., 2021). A more collaborative approach also included connecting participants with sensor designers/developers to co-create devices and engage in specific citizen-led campaigns (Mahajan et al., 2021; da Schio, 2020; Haynes et al., 2019).

3.4.5. Participant involvement via smartphones

Smartphones allow easy involvement of a high number of participants and instant delivery of results in real time. While low-cost sensor devices also allow large-scale deployment (Perelló et al., 2021), researchers usually have a limited number of devices and other resources available. In addition to participants already owning a smartphone, smartphone apps also allow flexibility in terms of level of participation. Participants can use them either passively to collect data or be more involved by inserting data and observations or by responding to surveys. They allow participants the option to adjust and regulate their involvement level, e.g., in the case of GPS privacy settings. The majority of the papers described a crowdsourcing approach.

Direct involvement can enhance learning and environmental awareness, and the use of focus groups and surveys can increase the level of participation as well as valuable feedback to scientists (Sîrbu et al., 2015).

3.5. Ethical and intellectual property issues

3.5.1. Ethics boards

Ethics boards and their mandatory approval are a key development in modern research that, at least in theory, provide protection to participants in research. This process is often criticized, with many calling for a more collaborative approach (McAreavey and Muir, 2011). Journals often require a statement on the approval of an ethics committee to be included in a submitted manuscript if the research dealt directly with participants. A fifth of the papers address these aspects. Although most of the papers deal with personal sensors for data collection, and some specifically address health status and related topics, in most cases ethical considerations are not mentioned. This lack of reporting can also be attributed to the discrepancy of ethics reporting rules in different countries and years.

A select few papers mention an independent external board or commission comprised of experts from appropriate fields that approved the study. Some studies involved an internal board or committee within the organization conducting/proposing the research.

3.5.2. Data protection and privacy

This section explores data protection and privacy issues in regard to EU and international regulations, e.g., referencing the General Data Protection Regulation.

A third of the papers discuss or mention data protection and privacy. Several options to obtain informed consent from the participants are referenced, e.g., participants provided their consent online (via web (Zhang et al., 2014) or app (McEwan et al., 2020)) prior to the start of the study or immediately after scheduling a meeting or were mailed a hard copy of the form. Regarding privacy policy, one protection measure was to ensure that access to databases was limited to a specific group of people, e.g., medical researchers administering the project (Laurino et al., 2021). Several papers discuss the privacy issues related to GPS data, which can be replaced with time–activity logs (Barkjohn et al., 2020), anonymized and aggregated into larger spatial cell units (Leao et al., 2014; Uejio et al., 2016), or actively recorded only when a person is in or near a specific space (Mears et al., 2021). Similarly, AQ data and/or activity data stored on a data server were not made visible publicly (Hu et al., 2014a), or participants could decide which information could be shared (Zhang et al., 2021). To provide an extra layer of privacy protection, data sets were protected with passwords, e.g., including for end users (Rebeiro-Hargrave et al., 2020).

3.5.3. Intellectual property aspects

When citizens are involved in research based on citizen science and co-design principles, intellectual property perspectives, according to Scassa and Chung (2021), can be considered based on four broad categories, depending on the nature and level of their inclusion: (i) classification or transcription of data; (ii) data gathering; (iii) participation as a research subject; and/or (iv) the solving of problems, sharing of ideas, or manipulation of data. With the increased levels of inclusion and contribution, intellectual property questions in terms of inventorship or authorship are becoming more important.

Intellectual property was addressed in some capacity, generally considering the technology used in the research, e.g., a general declaration of the source of funding for a specific technology used (Grossberndt et al., 2020), creating a company and the transfer of technology rights (Lefevre and Issarny, 2018), or using a trademark symbol when mentioning the technology (Dalla Valle et al., 2017). Seresinhe et al. (2019) dealt with pictures collected by citizens with an app and stated that the photos taken were the intellectual property of the photographers and not of the app they submitted them to. This opens up questions on the authorship of ideas and the contributions of citizen scientists in research.

4. Discussion

The lessons learned from the literature review are analysed through four general phases of the waterfall methodology (Ruël et al., 2010) of personal monitor applications for exposure assessments. These lessons are summarized based on the natural progression of a project in sequential form. Each phase is structured as follows: (1) definition of the stage and the inclusion of related reviews, (2) general findings and conclusions based on the literature reviewed, and (3) a short reflection and identified gaps. The following phases are elaborated (4D):

- phase 1 – DEVISE: defining the context of use and needs
- phase 2 – DESIGN: tool and protocol selection
- phase 3 – DEPLOY: engagement and data collection
- phase 4 – DEMONSTRATE: data analysis and implementation of results

The waterfall methodology (Ruël et al., 2010) used in the discussion is adapted from the field of project management, where several distinct and sequential phases exist within a project, e.g., scoping, design, development, testing, and deployment. This approach allows observation and critical evaluation of each phase (in the case of this review the 4D phases), and an opportunity to identify gaps and needs, and provide recommendations for future research.

4.1. Review matrix

Results of the review, focusing on the general outcomes, gaps, and needs, have been collected in a matrix, shown in Fig. 11. Overarching themes and characteristics have been identified and are listed in green text in each respective phase and evaluation criterion. Similarly, more specific conclusions and gaps are shown in black text. Phases and criteria often overlap and coincide, though this matrix offers a more methodological and delimitated presentation of the results.

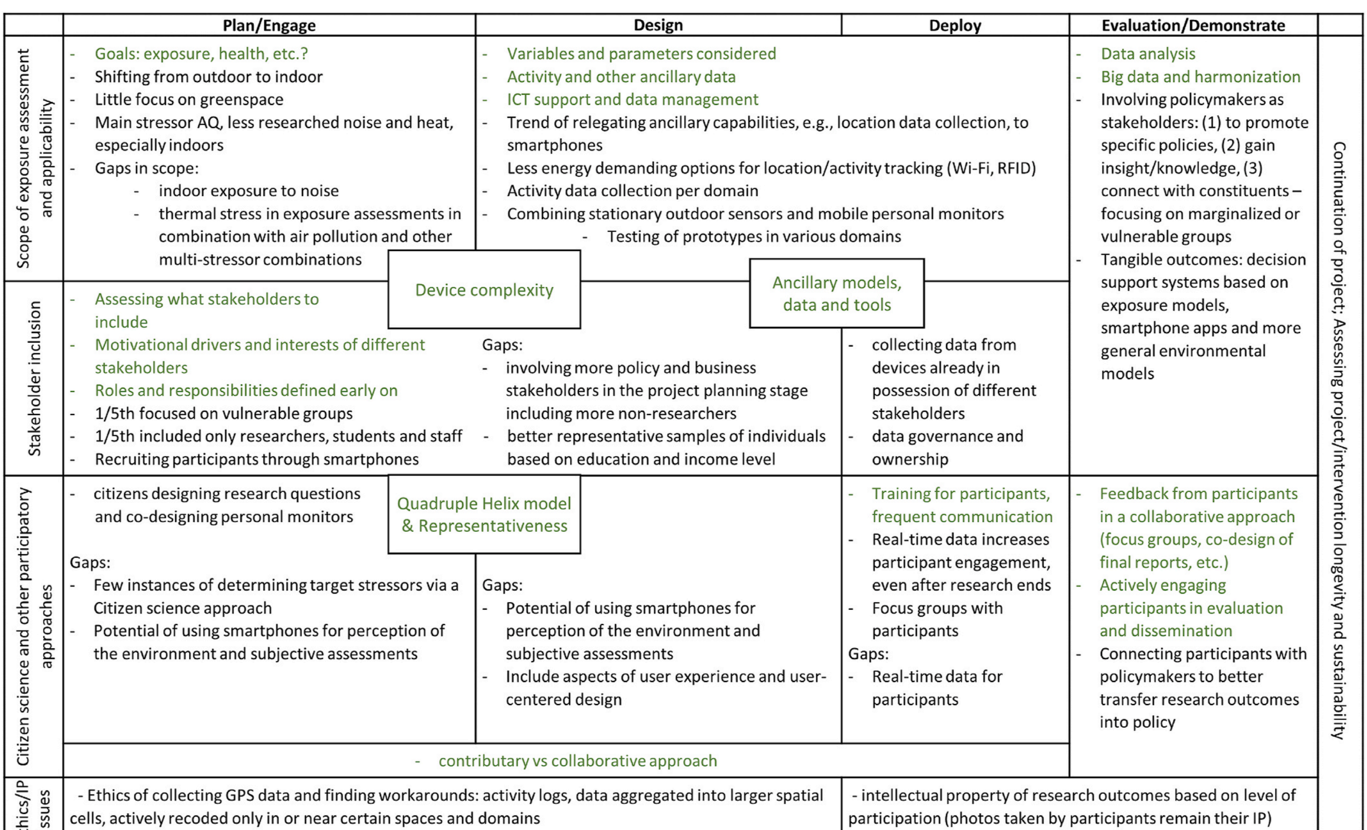

Fig. 11. Matrix with results of the review. Green-coloured text represents more general aspects and important keystones in each respective category. Other, more specific outcomes are in black text, and specific gaps are addressed separately.

4.2. Phase 1 – defining the context of use and needs: DEVISE

Devising an inclusive, multi-stakeholder plan defines Phase 1. Aspects considered in this phase include: (spatio-temporal) definition of the study domain, integration of information from various sources, assignment of roles for stakeholders involved, co-creation and participant involvement, etc.

Multi-domain assessments have become more common. Simultaneously collecting data in indoor and outdoor environments has become more pertinent, as people spend a majority of their time indoors. AQ is described as the main and important stressor (indoors and outdoors) in most papers. Noise exposure is focused more on outdoor and traffic proximity domains, and more thorough insight into noise exposure indoors is lacking. There is also a gap in studies addressing the combined effect of thermal stress and exposure to air pollution or other multi-stressor combinations. Personal monitors provide new opportunities for research to move into a direction of multi-domain and multi-stressor approaches. Moreover, these approaches can provide research results/outcomes that are more comprehensive and robust. Importantly, while almost all studies focused on urban stressors, less than half collected data on the specific activities of the participants and provided context for exposure. Several papers report on using technological advances to somewhat offset the issue of a large number of participants. Future research should lean in to these approaches, and utilize extensively the time and effort-saving technologies for collecting data on activities and microlocations, e.g., by using smartphone apps, GPS, Wi-Fi, and similar. External data sources also show promise in reducing cost while keeping the same level of complexity. These can be automatically collected and integrated into data streams, though they were not frequently used in the studies considered in this review.

Per the review outcomes, the motivations and expectations of different stakeholders have been analysed based on relevance criteria, following Robinson et al. (2021). Clarity of project/study aims, as well as managing expectations early on in the process are crucial when multiple stakeholders are participating (Robinson et al., 2021), as ill-defined aims can lead to conflicts and poor communication.

The quadruple helix model of stakeholders presents an inclusive framework. Representatives of citizens, industry, public authorities, and academia bring, and make use of, their own experiences, skills, knowledge, and networks. Results show that stakeholders from academia and research are most frequent, followed by society and NGOs, while policymakers and the business sector are rare. Though civil society and NGOs are stakeholders in several studies, they are generally a source of participants or used as recruiters. Researchers should utilize the benefits of a diverse set of stakeholders, as complex urban environments often include variables and confounding factors that can be overlooked. Involving participants in all stages of the project and its products, (depending on the aims of the project) makes research more accessible, relatable and understandable to communities that will be most impacted by the outcomes. However, papers rarely describe the involvement of participants in co-designing research questions, determining target stressors, and defining research methods. Government institutions and policy makers are primarily engaged as funders or external consultants. Private sector involvement is rare, though some cases show that this can lead to new businesses based on research outcomes. The motivations of stakeholders vary. Society and NGOs are driven by their desire to take part and contribute in knowledge generation and improvements in specific environments. Governmental institutions collaborate to obtain support for their decision-making processes or access to concrete products and solutions. Knowledge transfer to policy has become a key incentive in designing research and interventions in urban environments. By involving participants in several aspects of the research, while simultaneously collaborating with governmental stakeholders, there is an increased driver/facilitator to implement policy changes.

4.3. Phase 2 – Tools and protocols selection: DESIGN

Phase 2 – design is born out of the planning phase and considers tools, e.g., personal monitors, models, apps, and protocols, for data collection, including providing data for evaluating health outcomes. Several (low-cost) sensor systems are available on the market and are designed as either portable or static. These devices can measure multiple parameters, including geolocation, AQ, noise, and temperature. Commercially available devices usually transfer data via a smartphone/Bluetooth or directly to the cloud. In addition, it has become easier to assemble a low-cost monitor, adapted to the specific requirements of the research. Aspects commonly of interest to researchers include data reliability and control over quality analysis and quality control, access to raw data, insight into the algorithms used, and protocols for data capture and transfer. Although this "DIY" approach offers more customizability, it is necessary to consider end users and to design a non-intrusive monitor (e.g., avoiding frequent charging and dealing with connectivity and data storage and transfer issues). End users might also include researchers or field workers, and the design of the device should also include their needs in relation to handling with the device or retrieving data. A careful evaluation of the availability of personal monitors on the market should be conducted in the design stage of the project. Based on the results of the review and experience of the authors, these aspects, among others, should be considered:

- Are the devices on the market already fit-for-purpose as they are or with minor requirements of adjustments?
- Could the providers of commercial devices accommodate some of the additional requests, e.g., provide an in-app option to record a higher temporal resolution of GPS data?
- When a DIY approach is used for personal monitors, should some user-experience testing be included? It is important to acknowledge that, like with other aspects of participant-based research, that there is a limited pool of participants available, and a negative experience with a device or series of devices could discourage potential participants from collaborating in future studies.

For the purpose of exposure assessment, the collection of ancillary data such as activity and microlocation/microenvironment data in combination with modelling tools such as AQ or noise spatial maps can be employed. Several studies integrated ancillary data when employing multiparametric monitoring, where they combined data from various types of sensors, stationary/fixed, wearable/portable, intake analysis (such as monitoring breathing rate), location/activity logging, as well as qualitative measurements aiming at capturing subjective evaluations. Based on the collected data, several recommendations for future research can be made:

- By collecting ancillary data, e.g., activity and microlocation/microenvironment data, research results can provide a more comprehensive understanding of exposure and improve the accuracy of exposure assessment.
- Integrating multi-sensor data, including stationary/fixed, wearable/portable, and intake analysis, can provide a more varied look at exposure, and identify possible sources of urban stressors.
- Modelling tools, e.g., AQ or noise spatial maps, can be used to identify patterns and trends in exposure and make predictions about future exposure levels.

Qualitative measurements and subjective evaluations, can provide a more nuanced understanding of exposure, and include aspects that sensors do not capture (e.g., experiencing more stress by certain noises than others, even when the sensors show the same level of noise). This is particularly of interest when considering individual's health and well-being.

Phase 2 can also include collecting data for evaluating health outcomes. Most studies assessed perceived health and wellbeing, as they evaluated how participants perceived their health and how this perception was related to measured urban stressors. These outcomes, among others, were generally assessed qualitatively through detailed or semi-structured questionnaires, interviews, or smart phone applications. Studies can include biometric data, such as heart rate, respiratory rate, and physical activity levels, that can provide valuable information about an individual's physiological response to exposure. Combining biometric data with perceived stress can introduce a more nuanced view of exposure-related health outcomes.

4.4. Phase 3 – engagement and data collection: DEPLOY

Aspects considered in the deployment phase are multifaceted and include discussions of challenges with non-expert stakeholders, access to monitoring technology, research representativeness, intellectual property, and privacy issues. When non-expert stakeholders are engaged, there are several challenges to be considered. Froeling et al. (2021) analysed some of these challenges, applicable to participatory environmental monitoring projects. Several conclusions can be drawn based on the reviewed literature, reflected within the challenges previously outlined by Froeling et al. (2021):

(i) Expertise required by participants: Review results show examples of providing participants with the necessary training, keeping in touch throughout the sampling period, and being open to questions and possible modifications to the study protocols. Including participants as an equal stakeholder in research design and implementation provides an opportunity to identify more issues that could be addressed and which are of interest to the local community. Focus groups also provided an opportunity to gain insight, pre, during, and post the sampling period. A structured focus group can discover flaws in research communication and dissemination by directly observing and commenting on the approaches used. Involving the non-professional public also means, among other things, the risk of biased and unreliable reporting, data collection, and analysis. With this in mind, there should be a manual or machine-driven process of checking if this input is valid and appropriate.

(ii) Issues regarding available monitoring technologies and data quality: Studies in this review used apps and other technical solutions to alleviate some of the pressure on researchers to train participants. The results indicate that involving participants with real-time data increases their engagement, even after the research ends. On the other hand, a more involved approach by participants puts additional pressure on researchers to provide some kind of feedback, as the participants see their involvement as more integral to the research project. If the research enables real-time data to be presented to participants, this could be advantageous to both groups – participants and researchers. By providing real-time data, there is less of a need to compile and deliver extensive user data reports, and at the same time participants can analyse their own raw data autonomously.

(iii) Statistical representativeness of participating citizens: A classic problem in participatory research is achieving true representativeness of the general public by the selected group of participants, which can directly affect the usefulness of the results and their generalization and upscaling. Most of the studies that provided information on target groups considered all residents in an area, while some involved exclusively participants from a vulnerable group, e.g., children, the elderly, or people with disabilities. A fifth of the studies primarily employed researchers or students. The issue of poor representation could be offset by expanding participant recruitment to a diverse group of stakeholders involved in the research. With the inclusion of a diverse set of stakeholders from all quadruple helix groups, a wider pool of participants becomes accessible. Moreover, this approach can ensure and that the interests and needs of different groups are represented, leading to more inclusive and equitable decisions throughout the study design and implementation.

(iv) Data governance and ownership: At the outset, it is necessary to clearly define the conditions of data management, data ownership, as well as the intellectual property derived from it. Four papers discuss intellectual property issues. One study considered the intellectual property of photographs taken for the purpose of the research. Photos were the intellectual property of the photographers/participants and not of the app they submitted them to. The changing role of citizens from passive data collection or being just a subject of research to active participation in research also calls for changes in ethical guidelines. To this end, Ficorilli et al. (2021) call for the inclusion of new elements in various sections of classical ethical approvals, study protocols, information sheets, as well as informed consent.

4.5. Phase 4 – data analysis and implementation of results: DEMONSTRATE

Evaluation and reflection on data gathered in collaboration with all stakeholders follows the data collection phase. This phase entails reflection on the level of citizen science actually reached and the assessment of applications, demonstrability, and tangible outcomes. Citizens and urban communities are, in most cases, targeted as the main beneficiary of the research outcomes. On the other hand, laypeople do not necessarily have the necessary skills to conduct research. This is evident in the studies, as a majority of them included citizens as data collectors – crowdsourcing. Several papers report a higher level of involvement where participants were interviewed or invited into focus groups. This, in turn, provided additional feedback to researchers on how to communicate with and prepare participants to accurately collect data. By engaging participants more, researchers can communicate more effectively. In turn, this reduces the need for additional resources and effort.

As exposure assessment research evolves, it should include applicability and demonstrations of use in urban environments. Tangible outcomes can be included as an indicator on how well the research provides wider uses in planning, policy making, exposure reduction, and other aspects. Half the included papers reported tangible outcomes, with most of these being various monitoring systems, smartphone applications, or environmental models. Models dealt with AQ, taking advantage of new sensing technologies to improve resolution. The final users of research outcomes and products are usually policymakers. Some papers implied, that certain tangible outcomes were produced, though they did not list or describe them in the paper or link to any additional sources. More demonstrations of how tangible outcomes are produced and disseminated would be a welcome addition in literature of this topic.

This review showed that exposure research often does not include the "demonstrate" step. Usually, participants and other stakeholders receive a set of data or different models or test cases, not accompanied with a demonstration. An effective way of demonstrating the applicability of results is by engaging citizens. They can interpret and communicate further on their own, which can result in behavioural changes and consequently translate into policy measures (through bottom-up approaches) and, into changes in their local community. Demonstrating the conclusions of the research to participants is not necessarily in the scope of each research. Those that do include this aspect should consider a more inclusive approach to 1) better argue the relevance of their research, 2) induce behavioural change in individuals and local communities, 3) more effectively transfer research to policy and potentially ensure funding for future public-funded research, and 4) provide future incentives to recruit participants from a diverse pool and reduce biases.

5. Conclusions

A review of 86 papers relevant to the topic of individual-level exposure to urban stressors was performed. A waterfall model was used to assess the scope of exposure assessments, inclusion of stakeholders, citizen engagement and participation, and ethical and intellectual property aspects. Multiple trends, gaps, and needs were identified. Air pollution is the primary stressor assessed, followed by noise and heat stress. Multi-stressor evaluations are rare, as are studies that include activity and movement data to contextualize exposure. Future studies should address a lack of multi-stressor and multi-domain approaches for exposure assessment, in order to provide a more comprehensive overview of exposure to urban stressors. Devices used in individual-level studies are often designed for the specific study or sourced commercially. When designing sensors within a project, a user-centred design should be employed, having in mind the participants using the device and researchers/field workers accessing the data. Providers of commercial devices can often accommodate researchers with specific requests, and this is something worthwhile enquiring about before designing work-arounds.

With regard to stakeholder involvement based on the quadruple helix model, most are engaged from the general public/NGO group, followed by government/policymakers and the business/private sector. Research based on urban stressors should strive to reach a diverse group of stakeholders, which (i) bring different perspectives and experiences to observe overlooked variables and confounding factors, (ii) provide new opportunities and connections with local communities, (iii) improve knowledge-transfer and influence policy-making, (iv) improve representation and widen the pool of possible participants, and in turn ensuring more inclusive and equitable decisions. Citizens are rarely involved in a project before or after data collection, though certain examples show that a more involved approach boosts engagement and motivation, even after the research has been concluded. Engaging citizens and policymakers also helps to improve communication effectiveness, offers more opportunities for transfer of research to policy, and can aid the identification of issues in the local community that would be of interest for future research.

Tangible outcomes and demonstrations often include improvement of existing exposure models or the development of new models, as well as advancements in smartphone application design.

From the study review conducted, it can be concluded that enhancements in sensor technology and increasing public awareness of urban stressors have led to more efficient environmental and health risk management approaches and to solutions which will inevitably present a solid basis for improved public health in the future.

Funding

This document has been prepared in the framework of the European project URBANOME. This project has received funding from the European Union's Horizon 2020 innovation action programme under grant agreement no. 945391. This output only reflects the author's view and that the European Commission is not responsible for any use that may be made of the information it contains. Funding was received from the Young Researchers Program and the P1-0143 programme "Cycling of substances in the environment, mass balances, modelling of environmental processes and risk assessment", both funded by the Slovenian Research Agency.

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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.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to express sincere gratitude to Janja Snoj Tratnik, Jure Ftičar, and Miha Pratneker (JSI, Ljubljana), Vasileios Voulgarakis and Iliana Sousoura (VILABS), Christina Plomariti and Eleni Feleki (AUTH), Jaideep Visave (IUSS Pavia), and Guendalina Bettinelli (City of Milan) for their help with the review process.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.115685.

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