CITIZEN SCIENCE:
THEORY AND PRACTICE

Citizen Science for One Digital Health: A Rapid Qualitative Review of Studies in Air Quality with Reflections on a Conceptual Model

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ABSTRACT

The concept of One Health, a system-based approach that acknowledges the interdependence of human, animal, and ecosystem health, has grown in prominence over the past few decades. This transdisciplinary concept is increasingly important as the climate crisis, directly and indirectly, impacts all aspects of the planetary web of life. In tandem with the rise of One Health has been the increasing adoption of digital technologies into healthcare practice and within methods used to research human and environmental health. Emerging at the intersection of One Health and Digital Health is the idea of One Digital Health. This syncretic concept explores the opportunities that digital health presents to further the utility and operationalisation of One Health. A notable feature of the One Digital Health model is the role of citizen engagement. This feature aligns the digital approach with many One Health interventions that use citizen science to improve human, animal, and environmental health. This paper reports the results of a rapid review followed by a deep-dive into several representative studies exploring the intersections of One Health, digital health, and citizen science to identify new domains of innovative practice that supports resilience in the face of climate change and environmental health hazards. A focus on air quality reflects its importance in the One Health literature.

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INTRODUCTION

Global health threats, such as COVID-19 and climate change, remind us viscerally that we live in an interconnected world. Our environmental footprints degrade ecosystems, through urbanization, global travel, and agricultural land clearing (Rocque et al. 2021). Such disrupted environments compromise wild and domestic animal health and habitats leading to increased risks of pathogen transmission between animals and humans (Carlson et al. 2022).

The One Health concept arose within the infectious disease community, acknowledging the links between human, animal, and ecosystem health, particularly the importance of their dynamics for preventing disease and sustaining overall well-being (Gruetzmacher et al. 2021). The tripartite One Health collaboration between the Food and Agriculture Organization of the United Nations (FAO), the World Organisation for Animal Health (OIE), and the World Health Organization (WHO) has promoted adoption of this concept since 2008 (Gibbs and Paul 2014). In 2021, collaborating with FAO-OIE-WHO, the United Nations Environment Programme (UNEP) established the One Health High Level Expert Panel (OHHLEP) and adopted this definition for One Health:

> "One Health is an integrated, unifying approach that aims to achieve optimal and sustainable health outcomes for people, animals, and ecosystems. It recognizes that the health of humans, domestic and wild animals, plants, and the wider environment (our ecosystems) are closely linked and inter-dependent." (WHO 2021)

There is emerging recognition of the potential to use digital health technologies to increase understanding and improve interactions across the constituent systems of the One Health approach. Benis et al. (2021) coined the term One Digital Health to link society's digital transformation and the One Health movement, proposing that digital technologies contributing to human health can also be used to promote the health of ecological systems. Their One Digital Health framework encompasses digital interventions across the individual, population, society, and ecosystem levels, in five dimensions: citizen engagement, education, environment, human and veterinary healthcare, and healthcare industry 4.0.

The One Digital Health dimensions of citizen engagement and education are key elements of citizen science approaches. Broadly speaking, citizen science involves active forms of public participation in scientific knowledge production (Heigl et al. 2019; Haklay et al. 2021). It can facilitate environmental education and citizenship (Jorgensen and Jorgensen 2021), including climate justice, mitigation, and adaptation (Ceccaroni et al. 2020; Fraisl et al. 2022).

Citizen participation in both human health and environmental health research has been enabled by the ubiquity of the internet, personal mobile devices, and crowdsourcing platforms (Borda et al. 2019; English et al. 2018; Wiggins and Wilbanks 2019). However, technology-enabled participatory health initiatives that align with One Health (animal-human-environment) are not yet well described. The aim of this paper is to highlight practices and possibilities of citizen science for accelerating the adoption, and realizing the value, of One Digital Health. This paper focuses on air quality because it is a cross-cutting concern in One Health and critically illustrates digitally enabled citizen science addressing climate change adaptation (EEA 2019; Fraisl et al. 2022; McCarron et al. 2022).

METHODS

DATASET GENERATION

To address the evidence gap concerning the emergent One Digital Health concept, the authors undertook a rapid qualitative review of academic literature at the intersection of digital health technologies, environmental health, and citizen engagement. This rapid review led to the selection of 12 representative studies for deeper analysis to provide insights into the nuances of One Digital Health practice. This review type offers a timely and responsive approach to informing practice decisions and research plans. There is no standard method for a rapid review (Thomas and Harden 2008), with many studies adopting and omitting different elements of a systematic or scoping review method to meet the needs of their research question and context (Tricco et al. 2015). This review progressed in three stages as outlined in brief below and in Figure 1.

1. A rapid search of the literature was undertaken and screened.
2. A set of air quality studies was initially analyzed for their alignment with the One Health definition, their aims, outcomes, geographic location, and participatory method.
3. Twelve studies that represented unique insights into One Digital Health were identified, further analysed, and compared.

DATABASE SEARCH

The Web of Science, PubMed, Scopus, ACM Digital Library, and IEEE Explore databases were searched using variations of the following groups of terms: citizen science (e.g., crowdsourcing, community participation, participatory learning), digital technology (e.g., apps, mobile devices, gaming, sensors), and One Health (e.g., environmental health, exposome, climate change). See Appendix 1 for an example search strategy.

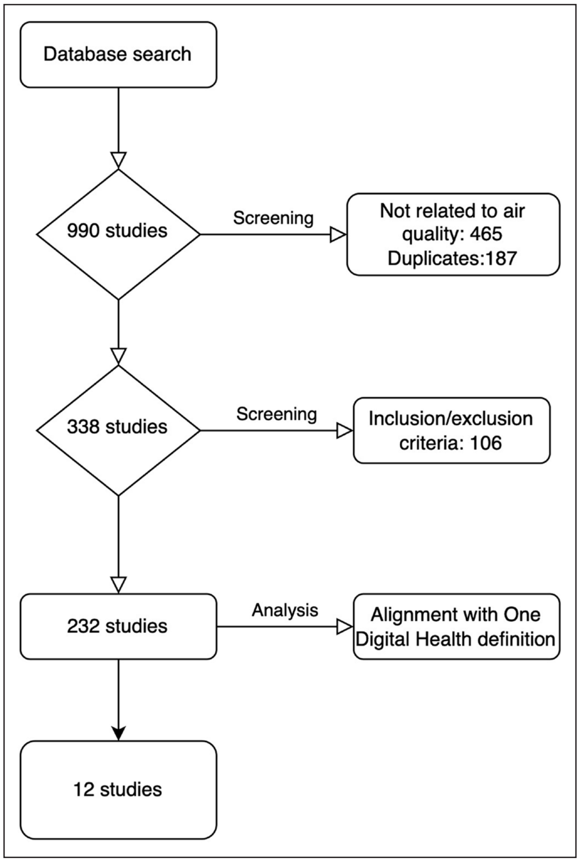

Figure 1 Search steps for the rapid qualitative review.

Searching was iterative and reflective focusing on (1) the purpose of the research, (2) the potential linkages among key concepts, and (3) how these might be articulated by researchers in diverse fields. The resulting articles were then hand-searched and associated online resources were further explored to identify additional literature.

These procedures resulted in an initial dataset comprised of 990 articles. At this point the authors determined that a more specific focus on air quality would be appropriate to ensure some coherent themes across the included studies and in consideration of the existing breadth of air quality research across environmental and human health (Box 1).

Box 1 Air pollution and One Health

Air pollution and One Health:

Air quality refers to the state of the air within our surroundings both outdoors and indoors. Air quality is determined by assessing a variety of pollution indicators, such as chemical, physical, or biological agents that modify the natural characteristics of the atmosphere. Examples include pollutants reaching high concentration levels, such as particulate matter (PM), carbon monoxide (CO), ozone (O3), nitrogen dioxide (NO2), and sulphur dioxide (SO2). Fine particulate matter of PM2.5 (particulate matter less than 2.5 micrometres) and PM10 (particulate matter less than 10 micrometres) pose the greatest risk to health globally (WHO 2006).

Air quality has implications for each element of the WHO One Health definition:

- Global awareness of air pollution and associated human health risks has grown significantly in recent years, often informed by citizens in their locales (Landrigan et al. 2018; EEA 2019) through "citizen sensing" enabled by low-cost portable sensors and do-it-yourself (DIY) open technologies (Pritchard and Gabrys 2016; EEA 2019; McCarron et al. 2022).
- Urban air pollution is linked to diverse human health conditions (Lelieveld et al. 2020). In 2015, around nine million premature deaths globally were attributed to diseases caused by air pollution (Cohen et al. 2017). Children, older adults, and those with underlying medical conditions may be particularly vulnerable through chronic exposure to PM2.5 (Landrigan et al. 2018; Mathiarasan and Hüls 2021).
- Indigenous peoples remain vulnerable to environmental pollution exposures from suburban sprawl and industrial development, including agricultural and extractive industries, waste dumping, and infrastructure and energy development (Fernández-Llamazares et al. 2020).
- Animals are known to experience cardiovascular dysfunction as a result of air pollutants (Losacco and Perillo 2018; Lederer et al. 2021).
- Air pollutants directly affect the photosynthetic activity, seed germination, and biochemical parameters of crops and other plants (Molnar et al. 2020; Ziss et al. 2021).
- Climate-related disasters can severely affect air quality. Smoke air pollution from 2019–20 Australian bushfires reached hazardous levels across rural and metropolitan areas (Rodney et al. 2021). The fires and their smoke caused nearly three billion animal deaths (WWF 2020).
- More polluted cities seem to have higher COVID-19 death rates (Ching and Kajino 2020). Such causal links have contributed to the concept of "One Air," in which air pollution is a link between environmental and human antimicrobial resistance (Abelenda-Alonso et al. 2021).

DATASET ANALYSIS

Upon applying relevant air quality filter terms (e.g., air quality, airborne, pollen, air pollution) to the results, 525 studies were identified and then further reduced to 336 after removal of duplicates. At this point, the title and abstracts of the included studies were screened using the inclusion and exclusion criteria (Table 1), leaving 232 studies in the final dataset.

The 232 studies were divided among authors TK, AB, and KW to identify and prioritize case studies most closely aligned with WHO's One Health definition. Rapid reviews and scoping reviews tend to rely on author-developed frameworks for extracting data (Biesty et al. 2020), so a structured template was created to capture study characteristics, alignment with One Health definition, and additional author notes about each study.

The 232 studies were already screened as being somewhat related to One Health based on their title and abstract. However, further textual analysis was required to identify whether individual studies had more than One Health intersection (i.e., among human health, animal health, and ecosystem health) or whether it combined human health behaviours and associated pro-environmental behaviours (i.e., caring for nature) (Jorgensen and Jorgensen 2021). Prospective alignment was also considered, that is, if the study described human pro-environmental behaviours or future actions that could lead to positive environmental intervention supporting animal health or ecosystem health. The authors charted the findings of this analysis in the template alongside other information about the studies such as the technology used, the geographic location, outcomes, and aims. This data analysis informed the selection of 12 representative studies for further examination (Table 2).

ANALYSIS OF REPRESENTATIVE STUDIES

The selected 12 air quality studies represent diverse approaches to air quality monitoring, and citizen and community participation (Table 2). For example, some focused on indoor versus outdoor air quality, while others explored changes in air quality due to specific events and circumstances. The intended outcomes from participatory air quality monitoring varied, too, from improving policy making to raising awareness of climate change impacts and promoting citizen behaviour change. Owing to the heterogeneity of the included studies, and rather than extracting every thematic variable that occurred in the data set, a deductive thematic analysis by authors TK, AB, and KW identified and agreed on key themes arising in the representative papers. This analysis sought to identify collective themes that were common across the papers and as a means of representing breadth of insight as to how One Digital Health functions in practice (Crowe et al. 2011). The deductive thematic analysis was guided by and reflected on elements of three related frameworks: (1) Benis et al.'s (2021) framework for One Digital Health described earlier; (2) Kieslinger et al.'s (2018) evaluation framework for citizen science projects that has three core dimensions of evaluation (scientific; participant; and socio-ecological and economic) and applies "outcome" and "impact" key criteria in each of them; and (3) Ruegg et al.'s (2018) Network for Evaluation of One Health framework that has four overarching elements: (i) definition of the initiative and its context, (ii) description of the theory of change with assessment of expected and unexpected outcomes, (iii) process evaluation of operational and supporting infrastructures (the "One Health-ness"), and (iv) assessment of the association(s) between process evaluation and outcomes produced. Informed by the three frameworks, the analysis supported the following dimensions that frame the synthesized findings: health context; digital technologies; citizen science methods, education and outcomes; and alignment with One Health.

FINDINGS

HEALTH CONTEXT

The objective of the representative studies was predominantly to examine the human health impacts of anthropogenic air pollutants. For example, chronic respiratory conditions, such as asthma, allergic rhinitis, and Chronic Obstructive Pulmonary Disease (COPD), were addressed directly in several studies. Specifically, the American Lung Association ranked Pittsburgh and its

INCLUSION	EXCLUSION
• Published before March 2022 • English language full text • Includes some elements of the WHO definition of One Health • Involves at least one example of citizen science or participatory methods • Involves digital technology supporting data collection, monitoring and/or analysis • Is a primary study	• Review studies, commentaries, editorials, secondary studies, conceptual studies • No use of digital technology • No One Health intersection: strictly focuses on environmental data AND environmental health, or human data AND human health, or animal data AND animal health

Table 1 Inclusion and exclusion search criteria.

CASE STUDY	ABOUT	LOCATION	CITIZEN PARTICIPATION	DIGITAL PLATFORMS	OUTCOMES
AirLouisville (Barrett et al. 2018)	A community program that used smart inhalers to help improve the asthma problem in Louisville	Jefferson County, Louisville, Kentucky, USA	1,147 Louisville residents aged five and above took part in monitoring using smart inhalers	Smart inhalers; mobile phone app Website: https://www.airlouisville.com/	Identified alternative truck routes away from high-risk neighborhoods; increased tree coverage; developed and tested an asthma forecast alert system
AirRater (Workman et al. 2021)	A study that evaluated user perceptions of AirRater's usability and effectiveness to help inform decisions about managing exposures to environmental health hazards	Australia: Tasmania; The Australian Capital Territory; and Port Macquarie, New South Wales	42 existing AirRater users participated in a pre-interview questionnaire, and semi-structured interviews	AirRater smartphone app Website: https://airrater.org/	Collected population health data via the app were utilized by AirRater collaborators with policy-making capacity in environmental health
CANAirIO (Valencia and Fonseca 2019)	A citizen science project that used mobile phones and low-cost technology to measure air pollution and other air indicators	Bogota, Columbia	Citizens assembled sensing devices, tracked air pollution episodes, and participated in raising awareness	The CANAirIO app and sensor kit Website: https://canair.io	Promoted citizen participation in air pollution monitoring; policy action towards reduction of fleet buses using diesel.
CAPTOR (Collective Awareness Platform for Tropospheric Ozone Pollution) (Schaefer et al. 2020)	An air quality research project that measured ozone levels, funded under the European Horizon 2020 Programme.	Italy; Austria; and Spain	Citizens engaged in three testbed regions in which 46 low-cost ozone measurement devices were installed outside citizens' houses to collect ozone pollution data	Monitoring stations; low-cost ozone measurement devices and apps, e.g., AirACT. Website: https://www.captor-project.eu/en/	Aggregated 5 actions by CAPTOR partners addressing priority challenges of EU environmental policies; 11 reports on air pollution and solutions, and advocacy
Citizen science for Air Quality Policy in Germany and Niger (Lepenies and Zakari 2021)	A multidisciplinary project that used citizen-generated data as an input for air quality policy and sustainable development goals (SDGs)	Leipzig, Germany; and Niamey, Niger	University of Niamey students responded to online quizzes and 10 surveys about air quality and SDGs and were involved in data /photo crowdsourcing campaigns on cooking technologies and fuels; small scale sensing and campaigning project in Leipzig	Multiple digital platforms, such as Google forms; portable low-cost sensors Website: https://globalyoungacademy.net/activities/interdisciplinary-grant-2019-20-citizen-science-for-reducing-exposure-to-urban-air-pollution/	Raised awareness that SDGs-aligned citizen science projects could close policy gaps; generated plans for upscaling and involving citizens in more phases of future projects
Citizen Sense (Gabrys 2017)	A project that documented the practices of residents engaged in monitoring air pollution near fracking sites in the US, as well as participatory research undertaken by the Citizen Sense project	Marcellus Shale region, Northeastern Pennsylvania, US	30 members of the public affected by the fracking industry in NortheasternPennsylvania engaged in air pollution monitoring and piloting different modes of data collection	DIY environmental and air pollution monitoring kit Website: https://citizensense.net/	Collected more than 5 million data points, and experiences of exposure to fracking sites; data used to lobby local government to address health impacts; created communities of care through multimodal ways of sensing and perceiving
Greater London Schools (Varaden et al. 2021)	A study that monitored air quality exposure of children wearing backpacks with special sensors, on their way to school and in the classroom	Greater London, UK	258 children (aged 7–11) from five London primary schools attended air pollution education sessions and measured air pollution using backpacks with built-in air quality sensors	Portable air pollution monitors and GPS tracking devices Website: https://www.london.gov.uk/WHAT-WE-DO/environment/environment-publications/breathe-london-wearables-study	Increased children's awareness of air pollution and led to adoption of positive behaviour changes

Swinomish Indian Tribal Community (Rohlman et al. 2019)	A community-based and Indigenous initiated study that measured personal exposure to polycyclic aromatic hydrocarbons (PAHs) and evaluated changes in knowledge related to air pollution	Southeastern Fidalgo Island, Puget Sound, Washington State, USA	25 adult non-smoking SITC Reservation residents (American Indian/Alaska Native) volunteered to wear a silicone wristband to learn about their personal exposure to PAHs and contribute data on PAH exposures in their community	A silicon-based passive chemical absorption wristband and automated ambient temperature collector Website: https://swinomish.org/resources/environmental-protection/dep-programs/air-quality.aspx	Increased awareness of ambient and indoor air pollution sources in the home, improved environmental literacy, and led to positive behaviour change to reduce possible exposures
PRAISE-HK (Personalized Real-time Air-quality Informatics System for Exposure – Hong Kong) (Che et al. 2020.)	A study that measured fine-scale air quality variations between streets and collected personal air pollution exposure details	Hong Kong (SAR)	Citizens and residents of Hong Kong region monitored and analysed their personal air pollution exposures.	PRAISE-HK app Website: http://praise.ust.hk	Resulted in a personalized air pollution tracking app helping users analyze their personal air pollution exposures from outdoors, and indoors and on different modes of transport, in support of Hong Kong's Climate Action Plan.
Schools and Weather Air Quality Network (SWAQ) (Ulpiani et al. 2022)	A citizen science project that placed meteorological and air quality sensors in its schools and engaged students in data analysis to improve urban weather and air quality measurements	Greater Sydney, New South Wales, Australia	Students collected and analysed research quality data for use in science and geography curriculum-aligned classroom activities	Distributed weather stations and sensors collecting and transmitting data Website: https://www.swaq.org.au/	Improved assessment of air quality impacts on Sydney schools from the Black Summer Bushfires in 2019–2020
Smell Pittsburgh (Hsu et al. 2020)	A study that crowdsourced smell reports to better track how odors from pollutants travel through the air across the Pittsburgh region	Pittsburgh and Allegheny County, USA	Residents of Pittsburgh and Allegheny County used the Smell Pittsburgh app to report outdoor odor pollution	Smell Pittsburgh app Website: https://smellpgh.org/	Generated more than 50,000 reports indicating odor pollution events in the Greater Pittsburgh region are related to the joint effect of wind directions and high hydrogen sulfide readings
Youth Engaged Participatory Air Monitoring: A Day in the Life (Johnston et al. 2019)	A community-driven participatory air monitoring program that focused on youth engagement	Los Angeles County, California, USA	18 high school participants from three community-based organizations wore portable personal monitors for a day, documenting and mapping their exposure to PM2.5 during their daily routine	AirBeams and AirCasting app; StoryMap for digital storytelling Website: https://keck.maps.arcgis.com/apps/MapJournal/index.html	Increased environmental literacy and enhanced knowledge of environmental justice among participants, including impacts of air pollution on humans and animals

Table 2 Case studies: summaries.

surrounds, the site of the Smell Pittsburgh project, as one of the worst-polluted areas in the US affecting lung and respiratory health (Hsu et al. 2020). The AirLouisville program arose from local public health concerns about high asthma rates (Barrett et al. 2018). Indoor and ambient air quality concerns triggered by an adjacent refinery petrochemical release and linked to noxious odors, burning eyes, irritated throats and lungs were the focus of the Swinomish Indian Tribal Community study in the US Pacific Northwest (Rohlman et al. 2019). Using cooking fuels and wood-burning inside homes was a problematic source of chronic respiratory conditions in Niamey, Niger (Lepenies and Zakari 2021). Harmful emissions from fracking in northeastern Pennsylvania, associated environmental disturbances, and their impacts on public and environmental health were highlighted in the Citizen Sense project (Gabrys 2017).

Air pollution as a proxy for health was evident in government and public health agency directives. For instance, European air pollutant concentrations often exceed limits set by the EU Air Quality Directives for PM_{10} and NO_2 (Schaefer et al. 2020). Varaden et al. (2021) noted that 400 primary schools in Greater London were in areas of high air pollution, exceeding the annual mean NO_2 EU Limit Values and PM2.5 concentrations. In the global south, concentrated levels of PM_{10} are the most significant air pollutant in Bogotá, Columbia, with about 50% related to vehicular traffic emissions (Valencia and Fonseca 2019).

Study locations represented high-, middle-, and low-income countries globally; comparatively less representation from the global south may have been due to the limitations of the rapid review. Most studies were in urban or peri-urban areas; whilst rural and remote areas were under-represented. The Swinomish Indian Tribal Community study (Rohlman et al. 2019) and the Citizen Sense project (Gabrys 2017) were located outside urban environments. Studies in low-income, racially and culturally diverse neighbourhoods, such as the Los Angeles County youth environmental justice program (Johnston et al. 2019) and CANAirIO in Bogota (Valencia and Fonseca 2019), reported the most degraded air quality, due to road systems or industrial sites.

DIGITAL TECHNOLOGIES

The availability of low-cost portable monitoring devices reported in the case studies, including consumer technologies such as AirBeams and open-source kits, support citizen self-assembly (Valencia and Fonseca 2019; Gabrys 2017). An earlier rapid review found that, compared with low-cost sensors, state-run sensor networks tended to have limited geographic coverage, raising citizen concerns about inaccurate local air quality assessment (Carvlin et al. 2017). The CAPTOR study undertook sensor validation and calibration at regulatory-grade air quality monitoring stations (Schaefer et al. 2020). In the Greater London schools' study, children carried backpacks fitted with sensors (Varaden et al. 2021). In the Swinomish Indian Tribal Community study, personal exposures to polycyclic aromatic hydrocarbons (PAHs) were measured using silicone wristbands (Rohlman et al. 2019).

Across the studies, smartphones were used for presenting and sharing air quality data among participants. In Smell Pittsburgh (Hsu et al. 2020), PRAISE-HK (Che et al. 2020) and AirRater (Workman et al. 2021), smartphones were used to crowdsource air quality data at specific times and locations. The AirLouisville smartphone app also incorporated data in the form of respiratory symptoms linked to a smart asthma inhaler used to record the number of "puffs" (Barrett et al. 2018).

Data collection from mobile and passive sensors focused on a common data point: particulate matter, i.e., PM2.5. Tropospheric ozone (O3) was monitored in outer urban areas, where air quality monitoring stations can be scarcer (Schaefer et al. 2020; Che et al. 2020; Workman et al. 2021). Apps used by volunteers to crowdsource localised air quality indicators provided data in some studies (Hsu et al. 2020). Monitoring stations were the main data capture and recording instruments in other investigations (Ulpiani et al. 2022; Schaefer et al. 2020). Some civic-funded initiatives used a combination of official monitoring stations and public-contributed data to support street level and personalised health monitoring needs, such as PRAISE-HK, which used fine-scale monitoring algorithms to detect air quality in outdoor and indoor settings, and on different modes of transport (Che et al. 2020). The integration of multiple data points, including environmental and public health data, also featured in the AirRater (Workman et al. 2021) and AirLouisville (Barrett et al. 2018) projects. The latter resulted in 1.2 million data points relating to particulate matter, combining more than 251,000 smart inhaler medication puffs with over 5 million environmental data points (Barrett et al. 2018). The Citizen Sense project (Gabrys 2017) compiled the most diverse digital and analogue dataset; the range of devices included custom-made fracking monitors.

CITIZEN SCIENCE METHODS

Initiators in the case studies represented place-based initiatives and public and environmental health policy and governance interests, resulting in a mix of collaborations involving university researchers, health agencies, and civic-government partnerships. In two studies, citizen instigators approached research experts to support their community air quality projects (Rohlman et al. 2019; Valencia and Fonseca 2019). Existing environmental literacy collaborations generated other community-focused projects, such as Citizen Sense (Gabrys 2017) and the Los Angeles County youth environmental justice project (Johnston et al. 2019).

Partnerships representing national agencies and/or government departments were indicative of projects with larger geographical coverage, such as CAPTOR (Schaefer et al. 2020) and AirRater (Workman et al. 2021). These were also aligned with the support of national government funding schemes and research priority areas. Most studies involved digital technology collaborators (universities and companies). For example, Smell Pittsburgh collaborated with the Carnegie Mellon Create Lab on its app development (Hsu et al. 2020).

Overall, the case studies did not significantly involve citizens in directly acting to improve air quality beyond data collection to highlight the potential impacts on human health or pollution avoidance behaviour, e.g., avoiding heavy traffic corridors (Varaden et al. 2021). There was an active public participatory focus in most studies, as guided by researchers towards testing air quality sensors, or in sampling and recording air quality using portable low-tech sensors to determine pollutant levels in neighbourhoods or urban centres. In some cases, there was more passive participation, in terms of hosting monitoring devices outside or inside the home, e.g., CAPTOR (Schaefer et al. 2020) and SWAQ (Ulpiani et al. 2022).

The duration of research projects recruiting citizen participants ranged from a day of citizen sensing (Johnston et al. 2019) to several months (Gabrys 2017; Lepenies and Zakari 2021). Data collection in over half the studies did not go beyond end of project funding; in one case, COVID-19 was a factor in the suspension of part of the study (Lepenies and Zakari 2021).

The numbers of participants varied from community-based initiatives (<20) to larger crowdsourcing efforts (< 1,000). Adults were the primary participants; however, a handful of studies involved children as citizen scientists in their neighbourhood and/or along school travel routes (Johnston et al. 2019; Varaden et al. 2021). AirLouisville was one of the few cases (Barrett et al. 2018) that recruited participants across age ranges with health vulnerabilities as citizen scientists, e.g., asthma and COPD. Citizen Sense recruited adult participants motivated by their speculative exposures to high levels of environmental hazards (Gabrys 2017), whether independent of their actual health problems.

Project-trained citizens were involved in building sensors in the CANAirIO (Valencia and Fonseca 2019) and Citizen Sense (Gabrys 2017) projects, as well as using them to independently record data, and then undertaking collective analysis to inform local government or policy makers (Lepenies and Zakari 2021). In some cases, citizens could download a publicly available app and record data or address a questionnaire about localised air quality (Hsu et al. 2020; Che et al. 2020).

Women in low socio-economic settings (Sorensen et al. 2018) and Indigenous participants were the least represented vulnerable groups whose health and livelihoods are potentially impacted by air pollution (Rohlman et al. 2019; Fernandez-Llamazares et al. 2020). The Swinomish Indian Tribal Community study, interestingly, had a higher proportion of female citizen participants (Rohlman et al. 2019), and the Niamey based study indirectly acknowledged women's exposure to pollutants through wood burning and cooking fuels in household exposures (Lepenies and Zakari 2021).

CITIZEN SCIENCE EDUCATION

Children and youth were commonly involved in environmental behaviour change studies and were activated through environmental literacy acquisition and/or environmental justice scenarios (Johnston et al. 2019; Rohlman et al. 2019; Kim and Sohanchyk 2022). The SWAQ program involved school students in collecting and analysing sensor data for use in science and geography curriculum-aligned classroom activities (Ulpiani et al. 2022). Children participating in the Greater London air quality monitoring project attended education sessions and focus groups with their parents, providing opportunities for collective learning, agency, and adoption of health positive behaviours (Varaden et al. 2021).

The AirRater app had mixed results in supporting participants' self-management of their health conditions (e.g., use of medication), but was successful in teaching participants how to reduce hazardous environmental exposures (Workman et al. 2021). Health self-management was a similar goal of the AirLouisville program; it provided training on the use of smart inhalers and a community Asthma Forecast alert system (Barrett et al. 2018).

Several community-based projects (Gabrys 2017; Valencia and Fonseca 2019; Johnston et al. 2019) involved participants in workshops covering a broad overview of air pollution with a focus on PM2.5 and its health effects. Both CANAirIO (Valencia and Fonseca 2019) and the Citizen Sense project (Gabrys 2017) also brought together citizens in workshops to co-develop micro-sensors and kits. As part of awareness-raising and dissemination activities among research communities and public members, some projects facilitated conferences, townhalls, and even exhibitions (Schaefer et al. 2020; Lepenies and Zakari 2021).

CITIZEN SCIENCE OUTCOMES

Project outcomes ranged from ways that individuals could reduce their exposure to concentrated levels of air pollution

(Rohlman et al. 2019; Workman et al. 2021; Varaden et al. 2021), to ways that health agencies could respond better to local air quality patterns (Hsu et al. 2020; Schaefer et al. 2020), to direct policy changes (Schaefer et al. 2020; Lepenies and Zakari 2021). Other developments include app enhancements, such as more fine-grained personalised environmental exposure features detecting exposure within a 2-metre radius of an individual (Che et al. 2020), and an app reward mechanism to further encourage use to reduce exposure to environmental health hazards (Workman et al. 2021). In the AirLouisville study (Barrett et al. 2018), citizen-generated data led to the adoption of policies to increase tree coverage in high-risk asthma areas, thereby reducing air pollutants and urban heat, and consideration of city-wide zoning changes allowing for air pollution emission buffers. The CANAirIO project (Valencia and Fonseca 2019) demonstrated how grass roots pressure from Bogotá's citizen collectives, using participatory sensing data, resulted in civic government reconsidering its decision to renew a fleet of diesel buses. The Citizen Sense project (Gabrys 2017) reflected on how air pollution policy could further be reconsidered in the context of shifting sites of care, going beyond addressing pollutant emission levels and considering ways in which exposure occurs and is experienced by participants living near fracking sites. The Lepenies and Zakari (2021) study and CAPTOR initiative (Schaefer et al. 2020) findings reinforced the need for participatory design measures to better involve citizens in all phases of future projects, such as designing research questions and protocols, data collection, analysis and dissemination.

ONE HEALTH ALIGNMENT

The studies were dominated by citizen science engagements addressing human health impacts, with ecosystem health a minor focus of data collection and engagement. One Health associations were not explicit in any of the case studies, but it was possible to glean pertinent intentions from those that generalised about their environmental health scope.

It was recognized that limits set for protecting human health and for exposures of agricultural crops and vegetation, for instance, to ground-level ozone (O3) and/or other air pollutants, still exceeded government objectives in certain instances (Schaefer et al. 2020). In some cases, ecosystem health supported human health through air pollution mitigation, e.g., nature-based solutions to increase plants or tree canopies (Barrett et al. 2018). Multidisciplinary collaborators in initiatives involving both public health and environmental health agencies reinforced that air pollution is complex in its derivations and impacts on human health and the environment (Workman et al. 2021). Similarly, projects initiated by citizens provided potential opportunities for mitigating actions with a One Health lens where communities were environmentally literate (Rohlman et al. 2019; Gabrys 2017).

There was a clear absence of attention to animal-human health intersections. Where impacts on animal health were mentioned, they were in the form of observations; for example, some participants noted the possibility of wider impacts of emissions on animals (dogs and other species) in the Los Angeles County youth environmental justice project (Johnston et al. 2019). The Citizen Sense project was unique in that it considered empirical, technical evidence of harm from fracking, e.g., air, water, and soil contamination, and it also argued that new forms of evidence of such harm should reflect the lived experience of non-human life across animal and plant communities and whole ecosystems (Gabrys 2017).

REFLECTIONS

The following reflections are drawn from the findings of our representative studies, highlighting further considerations of conceptual themes and emergent possibilities.

CITIZEN SENSING AND DIGITAL TECHNOLOGIES

Digital technologies can catalyse a more effective integration of human health systems with environmental and ecosystem health, as proposed in the Benis et al. (2021) framework. The increased availability of low-cost environmental sensors and smartphone apps enables citizens to collect empirical data on environmental concerns, such as air quality, whereas previously they may have accessed only proxy data (Roger et al. 2019). Digital health technologies also have a role in monitoring and mitigating localised environmental health-related changes of many kinds, for instance, due to natural disasters (Augusterfer et al. 2018; Haghi et al. 2022).

Questions about data quality, notably concerning low-cost sensors, hinge on the assumption that citizens' purposes for using them is to collect scientifically reliable data (Roger et al. 2019). However, data precision may be secondary to other goals, such as the engagement of citizens in discussion or behaviour change linked to their local environment (McCarron et al. 2022), or to supplement conventional data collection methods (Gabrys 2017; Johnston et al. 2019; Rohlman et al. 2019; Lepenies and Zakari 2021; Varaden et al. 2021). Participatory digital sensing can support public health and environmental health responses to air pollution challenges, giving agencies new community channels to communicate timely information and personalizing information to support individuals' decisions in response (Workman et al. 2021).

ONE HEALTH DATA POINTS

The Internet of Things, 5G networks, and smart devices create emerging opportunities to collect and share data about different environments in real-time (EEA 2019), e.g., as seen in the AirLouisville project (Barrett et al. 2018). These technologies offer the potential to link data collected across multiple systems, for example, human health and biodiversity data, as in the data sharing initiative of the Global Biodiversity Information Facility (GBIF). Limitations with sharing and standardization of data and lack of integrated analytical frameworks must be overcome to achieve wider and deeper data linkage (National Academies of Sciences et al. 2018; Nunn et al. 2021). A future review of citizen science work across biodiversity and conservation spaces could augment the learnings from the present review and fill identified gaps related to the health of fauna and flora. A complementary further review could examine how fairness in benefit-sharing from participatory data collection and analysis can extend to non-human entities (Gruetzmacher et al. 2021; Benis and Tamburis 2021; Nunn et al. 2021).

EMPOWERED AND COLLECTIVE PARTICIPATION

The need to overcome barriers between citizen science initiatives and upstream institutional policy formulation is clear (Lepenies and Zakari 2021). All parties must understand how project data and results can feed into policy debates and formation (Mahajan et al. 2022). Citizen councils and joint projects promoting citizen partnerships with policymakers are underdeveloped but could elevate citizen scientists' role in government advisory processes, for instance, where SDGs-aligned citizen science projects could close policy gaps (Lepenies and Zakari 2021; Mahajan et al. 2022). Air pollution was shown to be actionable with a mix of citizen, expert, and government agency stakeholders on board (Workman et al. 2021). This raises possibilities to extend policy-making processes through a One Health approach, encompassing more inclusive methods and outcomes such as found in health- and nature-based solutions (Hobbie and Grimm 2020). The Swinomish Indian Tribal Community study was framed around addressing air pollution of community concern, and in its effects on the whole environment. This decolonizing praxis enhanced community literacy, agency, and capacity, and followed an established institution-approved process as a transparent, ethically robust, indigenous community-controlled study (Rohlman et al. 2019; Calyx and Finlay 2022). In these regards, it succeeds in the aspirations of a more holistic One Health approach more than many such non-digital projects.

CONVERGING LITERACIES

Environmental health literacy incorporates community-specific knowledge and awareness of environmental risks, as well as the self-efficacy and skills for learning and implementing environmental and community action for systemic change (Lindsey et al. 2021). Digital Health Literacy (DHL), or eHealth literacy, has been recognized as a key attribute in understanding an individual's capability to use and benefit from digital tools and interventions to self-manage their health and make healthy choices (Norgaard et al. 2015). These study findings suggest that communities and individuals with greater levels of both literacies will be better equipped to prepare for and respond to air pollution–related health risks and health equity issues (Gabrys 2017; Johnston et al. 2019; Rohlman et al. 2019). These literacies can empower them to communicate risks, assess data, and comprehend uncertainty. Critically, they can make informed and responsible personal decisions, advocate for broader policies that protect wider health systems, and advocate for environmental justice and, potentially, One Health–aligned policies (Ceccaroni et al. 2020; Limaye et al. 2021; Mathiarasan and Huls 2021). One Health education has a further opportunity to enrich citizen science practice (Gabrys 2017; Rohlman et al. 2019) by encompassing all stakeholders, and by being acculturated with transdisciplinary knowledge systems and holistic approaches to planetary-level thinking (Villanueva-Cabezas et al. 2022).

NEW FORMS OF ONE HEALTH-ALIGNED ENGAGEMENT

The Gabrys study (2017) exemplifies the emergent concept of constructed communities of care around multimodal ways of sensing and perceiving, and the generation of new ways of acting towards healthier air, water, soil, and bodies. The technology and quality metrics were consequently less important than the collective community power that was generated. The inclusive and iterative process of community-investigator project co-development, and the different evidentiary forms of speculative harm combining digital and analogue tools, strengthened not just community engagement, but also agency to form, evoke, or provoke new modes of response. This process was also inclusive of non-human and not-yet scientifically categorized or captured perceptions, providing a form of voice to the "other" within the environment, whether animate or geographical (water, air, soil, plants, and animals). Similarly, the Rockefeller Foundation-Lancet Commission report, *Safeguarding Human Health in the Anthropocene Epoch* (Whitmee et al.

2015), initiated a shift from previously siloed approaches to improving human health to a knowledge systems approach to planetary health (Hancock and IUHPE Global Working Group 2021).

A CONCEPTUAL MODEL FOR CITIZEN-ENGAGED AND DIGITALLY ENABLED ONE HEALTH

The findings and reflections of this research have inspired our team to develop a new model (Figure 2) to incorporate how digitally enabled citizen science, in the One Health space, is initiated and progressed, as well as how it connects to various resource inputs and outputs. The model draws on the findings of this review, the One Health evaluation framework described in Ruegg et al. (2018), and the citizen science and public health framework described in Den Broeder et al. (2018) to articulate elements of One Health and citizen science that could be identified in future initiatives.

The conceptual model identifies the resource inputs that are shaped through citizen science activities and the potential outputs for communities, researchers, and the associated technology. For example, resources can include health literacy, local knowledge, and citizen participation. These resources are inputs to citizen science approaches to digitally-enabled One Health, yet also are reinforced, re-shaped, and strengthened through the process of participation. The outer circle of the model considers the various initiators of citizen science One Health projects and how they can overlap and influence one another. Initiators may include new policy agendas, health issues, new information, or technology. The second inner circle maps how different types of data and information practices are continually transformed into new information and knowledge (Godinho et al. 2021). These processes may occur across all three domains of animal, environmental, and human health, but when combined, they support multiple opportunities to co-create new knowledge within and between these domains. Thus, there is a strengthened ability to address local and global topics of One Health concern, such as air quality. Finally, the outputs of this process include increased capacity, new evidence and solutions, and improved communication.

LIMITATIONS

Methodological rigor in this paper comes from collaboration among four authors from varied disciplines reflecting together on the One Digital Health concept to shape an understanding of citizen science research. The inherent limitations of the rapid review and study analysis methods, as the basis for evidence in the

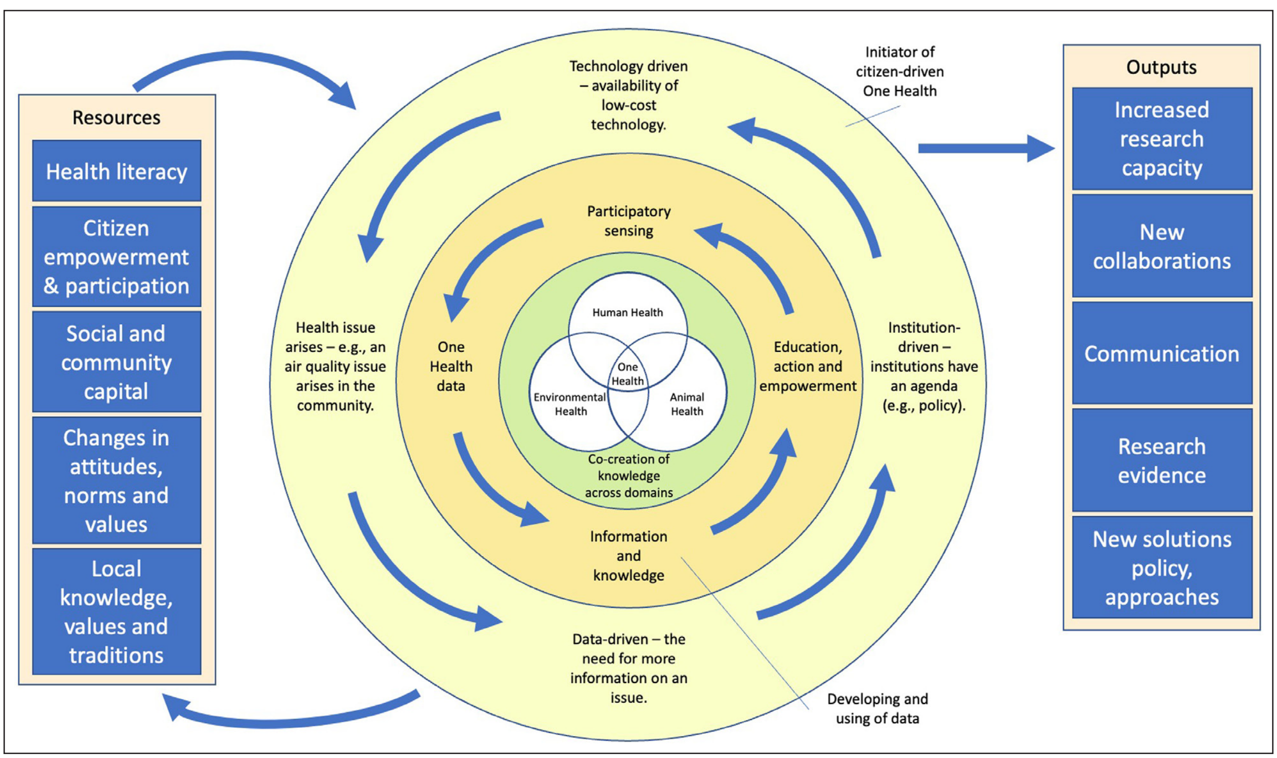

Figure 2 Conceptual model for citizen-engaged and digitally-enabled One Health.

multiple scientific fields with which One Digital Health citizen science engages, are acknowledged. Nevertheless, this approach respects their biopsychosocial and sociotechnical strengths. Likewise, the decision to focus on air quality limits the generalisability of the findings (Carminati 2018). However, this exploratory approach is justified by the relative newness of the research topic, combined with the sense of urgency raised by recent planetary climate health reports, to produce an initial basis for further research and practice.

There are also limitations in the conceptual issues underlying this review. The origins of the One Health concept, in preventing animal-human transmissible and communicable diseases and managing zoonoses, has limited its potential scope and application (Villanueva-Cabezas et al. 2020). One Health still lacks an ethical framework (Johnson and Degeling 2019; Garnier et al. 2020) and is challenged by its colonial, imperial, and military origins and affinities (Garnier et al. 2020; Coghlan et al. 2021; Calyx and Finlay 2022). Nevertheless, conscious of these historical debates, it is arguable that an ethical stance is still achievable and that the approach advances collective health (Johnson and Degling 2019). Indeed, one outcome to these discussions is the recent engagement with climate and environmental justice, as well as the foregrounding of the role of local traditional and ecological knowledge (Lysaght et al. 2017; Ceccaroni et al. 2020).

CONCLUSION

This paper highlights practices and possibilities for citizen science to strengthen One Digital Health via a close look at real-world citizen sensing in the air quality monitoring context. Much more of the One Digital Health concept needs to be translated into practice to attend to human-animal-ecosystem health, and to strengthen collectively the aims of communities and policymakers towards inclusivity. Building on the findings of this review, a conceptual model (Figure 2) has been developed as an initial articulation of how digitally-enabled citizen science can contribute to co-creating new One Health knowledge and practices.

The One Health approach creates a new space for collaboration among citizens and consumers of health, human health professionals (including digital health), and other broader health practitioners (Villanueva-Cabezas et al. 2022). Digital health and One Health are both moving at high speed in parallel but, so far, with little apparent convergence. The climate change crisis and COVID-19 pandemic offer new reasons to innovate and connect agendas (Chevance et al. 2020; Gray 2022).

This review calls for an urgent refocusing of how digital health and environmental health practitioners and policy stakeholders work with citizens. By adopting a One Digital Health approach to integrate the common aspirations across the human-animal-ecosystem health domains, there is the means to accelerate collective action for improved planetary health.

DATA ACCESSIBILITY STATEMENT

The search results and qualitative analysis are available on request. Please contact the first author for access.

SUPPLEMENTARY FILE

The supplementary file for this article can be found as follows:

- **Appendix 1.** Example Search Strategy. DOI: https://doi.org/10.5334/cstp.531.s1

COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

TK contributed to the conception, design, data collection, analysis and writing. AB contributed to the conception, design, data analysis, and writing. KW contributed to the conception, design, data analysis, and writing. KG contributed to the conception, design and writing.

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