CITIZEN SCIENCE:
THEORY AND PRACTICE

Methodological Diversity in Citizen Science Mosquito Surveillance: A Scoping Review

REVIEW AND SYNTHESIS PAPER

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ABSTRACT

Global concern regarding mosquito-borne disease emergence and re-emergence has driven the development of citizen science mosquito surveillance initiatives. Although these initiatives have shown great potential to assist local health authorities, ensuring outcomes are translatable to improved public health policy and practice remains challenging. Here we present a summary of citizen science mosquito surveillance programs worldwide, their focus, strategies, and outcomes, with a view to how best to apply this approach in their local areas. A scoping review of studies and reports was conducted through systematic search on electronic databases (Scopus, PubMed, Web of Science, and Google Scholar), grey literature, and other documents listed in the references of selected articles. A total of 33 citizen science studies included in this review described 29 citizen science mosquito surveillance projects operating in 16 countries, besides three programs with wide geographic coverage. The selected programs focused on different strategies and methods according to their local and national contextual needs. The majority of the programs reported being free or low in cost, and amenable to participants. Also, citizen scientists valued the opportunity to actively contribute to a scientific activity in which they saw value. Local and national programs have been successful in involving the broader public and yielding data on mosquito populations. However, to ensure the best public health outcomes, sustainability, and scalability, there is a need to continue engaging with stakeholders, including community members, researchers, public health agents, industry, and policymakers, and to bridge existing collaborations across different sectors.

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INTRODUCTION

Initiatives involving the community in monitoring the spread of mosquitoes, pathogens, and environmental changes are examples of successful partnerships between the general public and scientists (Roger 2019; Pawson et al. 2020; Braz Sousa et al. 2020). Such initiatives are identified as citizen science when there is an intentional community engagement and active public participation in scientific research. Citizen science is becoming more common and widespread within the scientific community as it both enhances the capacity for data collection and provides an opportunity for greater meaningful engagement between stakeholders, including community members, researchers, public health agents, industry, and policymakers (Roger 2019; Tarter et al. 2019).

The current COVID-19 pandemic has highlighted the importance of strengthened relationships between governments and public mobilisation to monitor and contain disease spread. Educational campaigns related to COVID-19 specifically have become more prevalent, and citizen science programs tracking the virus's spread are becoming popular (Katapally 2020). Public participation in scientific research can overcome logistical and spatial barriers regarding data collection and enhance outcomes by bringing local contextual problems to the discussion. Further, citizen science programs promote public understanding of science amongst participants (Bonney et al. 2016). There is potential for citizen science methods to be applied to other areas of need for public health benefit, such as the prevention of mosquito-borne diseases. Indeed, community engagement and mobilisation are part of the WHO pillars to tackle mosquito-borne diseases globally (WHO 2017).

Approximately 700 million people are infected by mosquito-borne diseases every year worldwide, and at least 1 million people die annually because of these diseases. These numbers may be much higher as diseases are still underreported in several countries (Beatty et al. 2011; Amarasinghe et al. 2011; Silva et al. 2016). Also, mosquito-borne diseases have a significant economic impact on the affected populations (WHO 2017; WMP 2021). With exotic mosquitoes introduced to new areas and lack of effective monitoring and control, such diseases are emerging and re-emerging worldwide (Bartumeus et al. 2018; Jones et al. 2021). Effective control of mosquito-borne disease requires surveillance systems that can report on the diversity and abundance of mosquitoes. Such surveillance typically makes use of specialised mosquito traps and trained professionals to identify disease-carrying species, so that control resources (such as measures to prevent mosquito bites and insecticide to reduce populations) can be deployed.

Citizen science initiatives in mosquito surveillance are expanding rapidly across the globe, enabling innovative methods to prevent and control arboviral diseases, and low-cost public participation and upscaling of traditional mosquito monitoring methods (Palmer et al. 2017; Braz Sousa et al. 2020; Carrillo et al. 2021). Advances in technology have enabled greater engagement in citizen science, and have facilitated interconnectivity amongst participants and researchers with sharing of real-time and geotagged data (Palmer et al. 2017; Caputo et al. 2020; Pawson et al. 2020). Adoption of new technologies has allowed citizen science programs to overcome some of the logistical and spatial barriers in data collection, and some methods can even provide real-time information regarding human mosquito encounter and nuisance (Bartumeus et al. 2018).

No study to date has compared the citizen science methods used for mosquito surveillance from a global perspective. Although some reviews were published in 2015, 2017, and 2018 highlighting the importance and impact of citizen science mosquito surveillance programs, they focused on the outcomes in Europe and North America (Kampen et al. 2015; Palmer et al. 2017; Bartumeus et al. 2018). A recent review of school-based citizen science projects (Abourashed et al. 2021) further highlights the potential for engaging the public throughout their life course.

Given the rapid expansion of these programs, it is also timely to review these programs and compare how other countries and continents are approaching this issue.

This paper presents a scoping review of the range, nature, and outcomes of citizen science mosquito surveillance interventions and programs globally. It further discusses the future of such programs as national implementations in their countries and how they could be integrated with formal mosquito surveillance programs.

METHODS

This review was conducted according to the Scoping Review extension of the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) statement and guidelines (Tricco 2018).

SEARCH STRATEGY AND ELIGIBILITY CRITERIA

We searched the electronic databases Scopus, Medline, PubMed, Web of Science, and Google Scholar, as well as the references lists of selected articles. This review aimed to identify peer-reviewed scientific literature and other relevant publicly available reports, published in English, describing citizen science mosquito surveillance initiatives (search strategy is presented in Supplemental File 1: Appendix 1).

We initially conducted a preliminary search on the aforementioned databases and found that interventions specifically named citizen science are relatively recent, the first one dated 2011. Indeed, the term citizen science was first introduced in the mid-1990s (Phillips 2018). In our pilot search, we found the earliest interventions involving the engagement of the public in mosquito monitoring dated from 2000, although these were not typically named as citizen science activities. For this reason, this scoping review included articles published from 2000 to March 2021, and databases were searched from February to March 2021. Keywords used in the electronic search, and inclusion and exclusion criteria, are presented in ***Table 1***. Grey literature included newspaper, magazine, and website articles as well as other published materials and other unpublished works (e.g., reports, infographics, posters, conference abstracts). This scoping review used the PEO (population, exposure, outcome) approach to frame the search strategy. PEO is often used to determine the association between specific exposures/approaches or risk factors and outcomes (Moola et al. 2015). In brief, this entails analysing each article to determine the population (e.g., city, group, state, district, etc.), the exposure (e.g., type of citizen science activity), and outcome (e.g., results of the work, findings, etc.). The search strategy involved main categories of terms describing citizen science and mosquito surveillance, as well as targeted time frame and language of the publication. The concept of citizen science has also been characterised as community science, crowd science, public participation in scientific research, volunteer-based monitoring, and participatory science (Carr 2004; Bonney et al. 2009; Miller-Rushing et al. 2012). As this approach has been named in different ways throughout past decades, we decided to include synonyms and other historical names in the search strategy. Further, most citizen science projects related to mosquitoes focus on the prevention of mosquito-borne diseases, as well as on the outcomes and benefits to public health. Thus, we included mosquito-related topics and some disease names in the search (***Table 1***).

SCREENING

All references were exported to EndNote X9 ® (2019, Clarivate Analytics, Toronto, Canada) for initial screening and to remove duplicates. After removing duplicates, the references were exported to Covidence ™ (2019, Alfred Hospital in Melbourne, Australia, Instituto de Efectividad Clinica Y Sanitaria (EROS) in Buenos Aires, Argentina) for screening. We screened the articles in a two-stage process, assessing the title and abstract as a first step and reviewing the full text as the second step. Screening was conducted by two independent reviewers (LBS and KLB). Articles were screened against the inclusion and exclusion criteria, and disagreements between reviewers were resolved through discussion. Reasons for exclusion included incorrect comparator, intervention, and/or study design (***Figure 1***).

Data extraction was conducted using a standardised template in Microsoft Excel (version 2017, © Microsoft Cooperation 2017). Data were extracted by one reviewer (LBS) according to the following fields: author(s), year of publication, origin/country (where the study was conducted), aims/purpose, study population and sample size, methods, intervention type and duration, comparator, outcome measures, and key findings.

RESULTS

A total of 1,027 articles were identified through the database search, and an additional 8 articles were identified through the grey literature search. After removing duplicates, 332 articles were imported from EndNote® to Covidence™. Fourteen additional duplicates were identified and removed in Covidence™, resulting in 318 studies being screened. After title and abstract screening, 269 articles were excluded, leaving 49 full-text articles for full-text review. A further 16 articles were excluded during full-text review (***Figure 1***).

After the final full-text screening, 33 articles were eligible for inclusion. These papers described 23 different mosquito monitoring programs involving community participation (Supplemental File 2: Appendix 2). Additional citizen science

CATEGORY	KEYWORDS
Citizen science	Citizen science, participatory science, community science, community engagement, community participation, public science
Mosquito surveillance	Mosquito, mosquito surveillance, mosquito monitoring, mosquito-borne diseases, vector, vector mosquito, infectious diseases, dengue, malaria, zika, arbovirus
Time frame	2000–March 2021
Language	English
Database	Medline, Scopus, PubMed, web of Science, Google Scholar, grey literature.

Table 1 Systematic search.

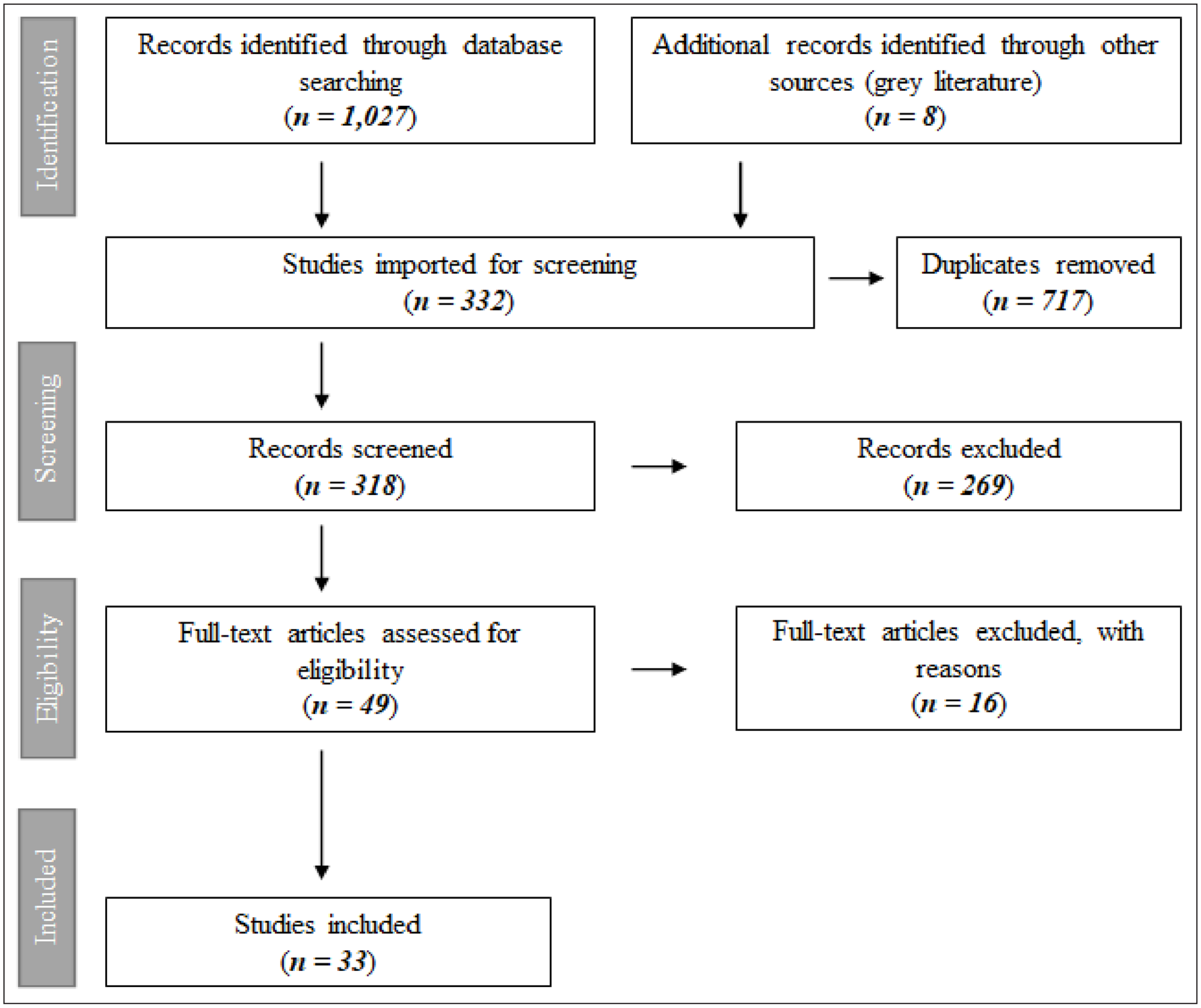

Figure 1 PRISMA extension for Scoping Reviews flow diagram showing the scoping review process for citizen science based mosquito surveillance programs.

interventions were identified through grey literature search, authors' knowledge, blogs, and citizen science platforms.

A total of 29 citizen science mosquito surveillance projects were found to be operating in 16 countries, besides three programs with wide geographic coverage. A summary of these programs is presented in ***Table 2***. Amongst these programs, 21 were explicitly identified by the authors as citizen science approaches, and seven were community-based programs and/or interventions not identified as citizen science in the published articles but considered as citizen science interventions in this review owing to the participatory nature of the interventions.

Although some programs did not refer to or categorise their approaches as citizen science, our scoping review identified several programs or pilot projects involving community-based interventions, community participation in focus groups to discuss their preference for specific interventions for mosquito control, and/or community mobilisation in identifying and eliminating mosquito breeding sites. Nonetheless, we considered some of these strategies as citizen science, as they involve the community in participatory research, and we present them in ***Table 2***.

The participants engaged as citizen scientists were the general public (86%) and school students (14%). Programs also combined either general public and professionals or general public and network of community leaders or village volunteers in mosquito surveillance activities.

In terms of the life stage of mosquitoes assessed, the programs focused on adult mosquitoes (55%), mosquito eggs (17%), mosquito larvae (10%), and pupae (7%). Also, programs focused on identifying and reporting mosquito breeding sites (24%), and breeding sites combined with dengue or malaria symptoms (7%). The targeted mosquitoes included Aedes mosquitoes (whether specific

	SURVEILLANCE SYSTEM TITLE	COUNTRY (STATE/CITY)	DURATION	PARTICIPANTS	TARGET MOSQUITO/S	SPECIMEN ASSESSED	SPECIMEN COLLECTION, REPORTING AND ANALYSIS METHODS	REF	URL
1	[a] *Mosquito Alert* (previously 'Atrapa el Tigre!')	Spain	2013/14 (Atrapa el Tigre!) and 2016–ongoing (Mosquito Alert)	Initially primary school students, later the general public	2013: *Ae. albopictus*; 2014–2019: *Ae. albopictus, Ae. aegypti*;	Adult mosquito	Using a smartphone application, participants sent geo-referenced images of target mosquito species to a research team. Received images were independently evaluated by experts and public health response measure mounted, depending on assessment findings.	Bartemeus et al. 2018, Hernandez et al. 2017, Pernat et al. 2021a	*mosquitoalert.com*
2	[a] *Mozzie Monitors*	Australia (South Australia)	2018–May 2019	General public	Non-specific	Adult mosquito	Participants were provided with a GAT trap for collection of mosquitos in urban environments. Participants photograph their catch and email the image to a research team for identifications. Participants reported data fortnightly.	Braz Sousa et al. 2020	*mozziemonitors.com*
3	[a] *Zika Mozzie Seekers*	Australia (Queensland)	2017–ongoing	General public	*Aedes* mosquitoes	Mosquito eggs	Participants are asked to set up DIY backyard mosquito egg traps, collect the eggs and send them in for molecular analysis. The program uses the PCR technique to detect traces of DNA of *Aedes aegypti* and *Aedes albopictus*.	Montgomery et al. 2017, Montgomery et al. 2020	*metrosouth.health.qld.gov.au/zika-mozzie-seeker*
4	[a]*Mozzie AR Toolkit*	Australia (Queensland)	2019–ongoing	Primary school students	*Ae. albopictus* and *Ae. aegypti*	Breeding sites	This program targets primary School children from Brisbane, QLD, Australia, using Augmented Reality (AR) as an interactive experience to encourage students to identify and manage mosquito breeding sites.	Seevinck et al. 2019, Seevinck et al. 2020	*mozziescience.wordpress.com/2020/08/03/mozzieart/*
5	[a] *STEM Champion Mozzie Hunters*	Australia	2019–ongoing	Secondary School students	*Ae. albopictus* and *Ae. aegypti*	Eggs	Students construct biodegradable traps to collect eggs of urban mosquitoes. Then, they learn how to extract the DNA and use open-source and affordable molecular technologies (real-time PCR) to identify the presence of exotic mosquitoes DNA in the eggs.	Seevinck et al. 2020	*mozziescience.wordpress.com/2020/08/06/scmh/*

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	SURVEILLANCE SYSTEM TITLE	COUNTRY (STATE/CITY)	DURATION	PARTICIPANTS	TARGET MOSQUITO/S	SPECIMEN ASSESSED	SPECIMEN COLLECTION, REPORTING AND ANALYSIS METHODS	REF	URL
6	[a]*Honiara Citizen Science*	Solomon Islands	2019	General public	Non-specific	Adult mosquitoes	Volunteers attended a training workshop and were provided BG-Sentinel traps to collect and type mosquitoes over an 8-week period of data collection. They also received a magnifying glass and a pictorial mosquito identification card. Participants sent SMS to a central authority to report count data.	Craig et al. 2021	
7	[a] *ZanzaMapp*	Italy	2016–2018	General public	Non-specific	Adult mosquito nuisance	Participants use a mobile phone app, ZanzaMapp, to share their perceptions of mosquito abundance and nuisance in Italy. Users share their records' GPS locations and answer four questions regarding the perceived presence, abundance, and nuisance of mosquitoes.	Caputo et al. 2020	*www.zanzamapp.it/*
8	[a] *The North American Mosquito Project* *citizenscience.us*	USA and Canada	2011–2012, 2014–2015	Mosquito control professionals, and later the general public	Not reported	Adult mosquito	Citizen participants were provided with traps and attractants, and asked to send the unsorted trap catch to a research team for identification.	Cohnstaedt et al. 2016b	
9	[a] *The Invasive Mosquito Project* (evolved from the North American Mosquito Project)	USA	2016–ongoing	High school students	*Ae. aegypti* and *Ae. albopticus*	Adult mosquito; mosquito eggs	Students placed germination paper in prepared containers to collect eggs laid by container-dwelling mosquitoes. Dried paper (with eggs attached) was taken by the student to school, where quantitative and qualitative observations were made and recorded. In addition, students (under teacher supervision) were encouraged to hatch a portion of the eggs and identify mosquito species using a picture key provided. Further, to confirm adult mosquito identification, students shipped specimens to the US Department of Agriculture (or a local or regional mosquito control partner).	Cohnstaedt et al. 2016a	*Citizenscience.us*

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10	[a] *Mosquito Stoppers*	USA (West Baltimore)	2014–2015	General public	*Ae. albopictus*	Adult mosquito	Participants completed up to four data collection tasks (i.e., questionnaires) designed to quantify *Ae. albopictus* habitat and population levels, and mosquito nuisance in their yards. Data was reported monthly for 6-weeks.	Jordan et al. 2017	*baltimoremosquitoes.weebly.com*
11	[a] *The Great Arizona Mosquito Hunt*	USA (Arizona)	2015–2017	Primary school students	*Ae. aegypti*	Mosquito eggs	Participants were provided with a kit that included instruction on how to make an ovitrap, germination paper, and alfalfa-based rabbit food to serve as an attractant. Participants set the trap and collected, dried, and mailed the germination paper (with mosquito eggs attached) to a research team. Received samples were inspected by an entomologist to identify *Aedes* eggs.	Tarter et al. 2019	
12	[a] *iMoustique®*	France	2013	General public	General, focusing on *Ae. albopictus*	Adult mosquito	iMoustique® is a smartphone app used to share information on mosquito presence. The app provided a simple three-step determination key to help people identify if the observed specimen is a mosquito. Users shared georeferenced photos of the observed mosquitoes.	Kampen et al. 2015	*www.eidatlantique.eu*
13	[a] *The Muckenatlas*	Germany	2012 -Ongoing	General public	Non-specific	Adult mosquito	Participants are required to capture resting mosquitoes using a closable container and to post killed mosquitoes with a completed questionnaire (that is available online) to a research team where they are identified in a laboratory using either morphologic or genetic methods. Identification of invasive species of interest are investigated and enhanced surveillance implemented, if required.	Pernat et al. 2021a, Pernat et al. 2021b, Walther and Kampen 2017, Werner et al. 2020	*Muechenatlas.de*

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14	[a] *The Muggenradar*	Netherlands	2014	General public	Non-specific	Adult mosquitos	Via a web-questionnaire, participants provided information on their experience with nuisance mosquitos, including the time/date and location of an incident. Participants were given the opportunity to submit a mosquito specimen for identification. Received samples were genetically analysed; results were not reported.	Kampen et al. 2015	*Muggenradar.nl*
15	[a] *Mosquito WEB*	Portugal	2014-ongoing	General public	Non-specific	Adult mosquito	Participants collect mosquitos in the environment and post them, together with basic information about the insect's collection location, to a research team who identified the sample using morphological and/or molecular means.	Kampen et al. 2015	*Mosquitoweb.pt*
16	[a] *TopaDengue*	Paraguay	2018–2019	General public	*Ae. aegypti*	Larvae, pupae and breeding sites	Community volunteers visited houses in their neighbourhood every week in specific months (dry and rainy) to inspect the presence of larvae and pupae *Aedes aegypti* and the type of container they were breeding. Volunteers used both paper and digital technologies to report the outcomes to researchers. As digital technology, they used the DengueChat interface to share data of breeding and entomological status.	Parra et al. 2020	
17	[a] Monitoring alien mosquitoes of the genus Aedes in Austria	Austria	2017	General public	*Aedes* mosquitoes	Mosquito eggs	Citizen scientists used provided ovitraps to monitor mosquito oviposition in their houses. They sent the samples to researchers for species identification through morphology assessment. Researchers can use DNA extraction and PCR for identification as well.	Schoener et al. 2019	

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18	[a] *GLOBE Observer*	Wide geographic coverage/ 93 countries	2016–ongoing	General public	Non-specific	Mosquito habitats/ breeding sites	GLOBE Observer is an ongoing NASA-sponsored citizen science mobile application. Citizen scientists download the app, complete interactive training to learn how to use the tools, and share their mosquito breeding habitat photos. GPS information, time and date of each observation are shared. Participants also answer some questions about surface conditions and report numerical estimates of mosquito larvae.	Amos et al. 2020	*observer.globe.gov/get-data/mosquito-habitat-data*
19	[a] Cit Sci in Rwanda*	Rwanda	2018	General public	Non-specific	Adult mosquitoes, malaria cases and mosquito nuisance	Volunteers were asked to report experienced mosquito nuisance and confirmed malaria cases in their houses. Additionally, the selected volunteers used passive mosquito traps to collect and submit collected specimens. More than 2,000 mosquitoes were collected throughout six months.	Murindahabi et al. 2019	
20	[a] Abuzz	Worldwide	2017–2018	General public	Non-specific	Adult mosquitoes – wingbeats	People were encouraged to record sounds of mosquito wing beats by placing their mobile phone microphones near the flying mosquitoes. People referred to brochures to learn how to record the sounds more effectively. They can point their phones to mosquitoes on the wall (and make them fly), to flying mosquitoes, or even to mosquitoes trapped in a bottle and record the sounds from the bottle walls. Records are uploaded to the Abuzz project website.	Mukundarajan et al. 2017	*web.stanford.edu/group/prakash-lab/cgi-bin/mosquitofreq/how-you-can-help/record-mosquitoes/*

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21	[a] *Citizen Action through Science (Citizen AcTS)*	USA	2016–2017	General public	*Ae. albopictus*	Adult mosquitoes	Citizen scientists purchased one or more Biogents-Sentinel (BGS) traps (Biogents, Regensburg, Germany) in their backyards to capture adult mosquitoes. The traps were operated for 24 h using 12 V rechargeable batteries. Trials included eight sampling events of 24 h each, over six weeks. Researchers counted and identified adult mosquitoes collected per trap.	Johnson et al. 2018	
22	[a] Crowdsource for Mosquito Sampling*	USA, Canada (plus outgrouped samples received Europe and Asia)	2011–2012	General public	*Ae. vexans or Cx. tarsalis*	Adult mosquitoes	People were recruited by mail, email, phone and word of mouth, and were invited to collect and send samples of adult mosquitoes. Recruited people received sample vials, traps, alcohol, and prepaid mailers on request. Contacts sent more than 1,000 specimens from 40 different provinces and states in Canada and the USA and from some outgroups in Europe and Asia.	Maki and Cohnstaedt 2015	
23	[b] *Mo-Buzz*	Sri Lanka (Colombo)	2015-ongoing	General public	*Ae. aegypti*	Dengue-like illness symptom and breeding sites	Through the Mo-Buzz smart phone application, participants report dengue-like illness symptoms, knowledge of mosquito exposure/visible bites, perceived mosquito density, and/or post pictures of potential Aedes mosquito breeding sites. Data received is time-stamped and geotagged and sent to health authorities, thereby stimulating a public health action.	Lwin et al. 2016, Lwin et al. 2019	

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24	[b] *Dengue Chat*	Nicaragua, Mexico, Brazil, Paraguai, Colombia	2015	General public	*Aedes* mosquitoes	Mosquito breeding site	Dengue Chat crowdsources information from the public through a smartphone application. Participants report the location of suspected breeding sites and provide photographic evidence. Data are shared with other users through the app or web interface. Community members can engage with each other and exchange information about dengue and chikungunya risks.	Coloma et al. 2016	*www.denguechat.org*
25	[b] *Camino Verde*	Nicaragua and Mexico	2004–2012	General public (supported by community leaders and facilitators, the "brigadistas")	*Aedes* mosquitoes	Mosquito larvae and pupae	Activities were facilitated by community volunteer leaders who received training (Brigadistas). They visited houses in urban and rural areas, and checked for mosquito breeding sites and the presence of larvae and pupae. Schools, churches, shops, clubs and other organisations were engaged in the effort as well. *Brigadistas* reported findings to the Centro de Investigación de Enfermedades Tropicales (CIET, Centre for Investigation of Tropical Diseases) and the University of California, Berkeley.	Arostegui et al. 2017, Hernandez-Alvarez et al. 2017, Ledogar et al. 2017a,b, Morales-Perez et al. 2017	*caminoverde.ciet.org*
26	[b] *Lansaka Model*	Thailand	2014–2015	General public (supported by a network of village volunteers)	*Aedes* mosquitoes	Mosquito larva	Household members inspected and recorded larvae in containers in- and outside their houses every day. The group leaders collated the data from village volunteers and provided it to the head of the village who provided the data to designated health authority. Data were entered it into an online database by the authority. Information derived from the data was reported back to the community through the network, and was advice on any public health action required.	Suwanbamrung 2018, Suwanbamrung et al. 2018	

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	SURVEILLANCE SYSTEM TITLE	COUNTRY (STATE/CITY)	DURATION	PARTICIPANTS	TARGET MOSQUITO/S	SPECIMEN ASSESSED	SPECIMEN COLLECTION, REPORTING AND ANALYSIS METHODS	REF	URL
27	[b] *Mosquito Reporting Scheme/Mosquito Watch*	UK	2005–2012	Amateur and professional entomologists, museums and universities and the general public	Non-specific	Adult mosquitoes	Interested participants sent samples of mosquitoes causing a nuisance to the Public Health England (PHE) for identification.	Kampen et al. 2015	
28	[b] *Patio Limpio*	Mexico	2007	Community leaders and the general public	*Aedes* mosquitoes	Breeding sites	Trained local residents (known as block activators) participated in community assemblies. Educational and informative materials were also distributed to the households during visits. More than 1,000 block activators received training, and they inspected more than 5,000 backyards.	Tapia-Conyer et al. 2012	
29	[b]Intersectoral dengue control in Cuba*	Cuba	2003–2005	General public	*Aedes* mosquitoes	Breeding sites	From 2003 to 2005, informal leaders from existing community organizations participated in Community Working Groups (CWGs). These members visited the houses in their local areas, surveying backyards and water storage containers (with the presence of the households). They monitored the presence of container breeding sites and offered options to protect or eliminate the containers.	Sanchez et al. 2009	

Table 2 Citizen science mosquito surveillance programs worldwide

[a]Citizen science–identified programs. [b]Community-based programs and/or interventions non-identified as citizen science in the published articles but considered as citizen science interventions in this review owing to participatory research. *No specific name for these programs/interventions.

or not to the Asian tiger mosquito Ae. albopictus and the yellow fever mosquito Ae. aegypti) (59%), and non-specific species (41%).

The methods used for citizen science mosquito surveillance included the use of smartphone applications to report data (28%) and traps or available containers to collect specimens (48%); one program used a dedicated website for participants to upload acoustic data of mosquito wingbeats, and seven programs surveyed breeding sites as methods (24%). One program focused on acoustic data of flying mosquitoes, and two programs also collected data of adult mosquito nuisance. As reporting strategies, participants sent photos of collected mosquitoes (17%), mailed specimens for identification (41%), and reported the findings (usually of breeding sites and larvae presence) to the local health authorities and/or researchers (17%) (list of methods and strategies per program are shown in Supplemental File 3: Appendix 3).

Amongst the fourteen programs using traps for data collection, four used ovitraps (traps in which female mosquitoes lay eggs), seven used adult traps, and three programs advised participants to use any available container at home to capture mosquitoes. Three programs used do-it-yourself (DIY) approaches, in which participants made their traps at home to collect adults or eggs. Six programs required equipment delivered to participants, provided at no cost, including a trap kit or material to make the trap. Only one program required participants to purchase the traps.

Great variation in program length was evident (**Table 1**). Whilst some programs are listed as ongoing (9/22. 41%), the majority were conducted over a period of 1 to 3 years (13/22, 59%). The North American Mosquito Project was a fixed-term program that was antecedent to the ongoing Invasive Mosquito Project, and as such is considered a single project in the aforementioned Table.

All studies in this review reported achieving their study aims, and the benefits afforded citizen scientists by their engagement can be understood through different socioeconomic and geographic contexts. Also, in the same program, households received feedback to take specific actions to manage mosquito breeding sites (Suwanbamrung et al., 2018). Also, facilitated engagement between citizens and scientists was reported in different programs and countries (Lwin 2017; Parra et al. 2020; Craig et al. 2021).

Citizen science mosquito programs have been developed in several countries, notably across Europe (Palmer et al. 2017), where six different programs exist. These programs assist local authorities in the monitoring of abundance and diversity of endemic mosquitoes as well as in detecting exotic mosquitoes (Tyson, 2018). Mosquito Alert, Mueckenatlas, ZanzaMapp and Mosquito Habitat Mapper are examples of current and ongoing projects in Spain, Germany, Italy, and the United States, respectively. These programs have shown a high level of impact, utility, and reliability when compared with traditional surveillance methods in these countries, allowing real-time vector reports, mosquito presence and abundance tracking, and exotic species detection (Bartumeus et al., 2018, Eritja et al., 2019). Also, community engagement in mosquito monitoring has brought unexpected outcomes in specific contexts, as recently observed in Spain where the occurrence of the invasive species Ae. japonicus was detected for the first time (Eritja et al. 2019). In the US, the GLOBE Observer program yielded data similar to the efforts of thirteen years of professional data collection in only three years of evaluation (Amos et al. 2020).

Mo-Buzz in Sri-Lanka focused on gathering information on community perception of mosquito density and dengue-like symptoms (Lwin 2017; Lwin et al. 2019). Dengue Chat in Nicaragua and Lansaka Model in Thailand are examples of local programs that collected data on breeding site distribution and the presence of larvae in the surveyed areas (Coloma 2016; Suwanbamrung et al. 2018).

In Australia, Mozzie Monitors and Zika Mozzie Seeker have been engaging the community in tracking mosquito presence and abundance, and in detecting exotic species. Mozzie Monitors is the first citizen science mosquito surveillance program in the world that combines fixed-point traps and public reporting in adult mosquito monitoring (Braz Sousa et al. 2020). This approach engages members of the community to monitor species of medical importance and increases knowledge of mosquito fauna across Australia. Preliminary studies have demonstrated that this program is as effective at recording diversity of mosquitoes as is the formal mosquito surveillance programs, and it costs only about 20% of the total budget estimated for the traditional methods (Braz Sousa et al. 2020).

Zika Mozzie Seeker is an initiative of Metro South Health (a local area network of Queensland Health). It has been running since 2017 in Queensland, Australia, where Aedes aegypti is established in the state›s far north region. The program engages community members to set up DIY backyard mosquito egg traps, collect the eggs, and send them to researchers for molecular analysis. To detect the presence of Ae. aegypti and Ae. albopictus in sample, the program uses PCR technology developed by Queensland Health (Montgomery 2020).

Also, pilot projects were described in the Solomon Islands and in Rwanda, aiming to identify the opportunities and challenges to establish citizen science–based programs in these areas (Murindahabi et al. 2019; Craig et al. 2021). The citizen science engagement in Honiara, Solomon

Islands, showed potential to upscale capacity for mosquito data collection locally. Participants also reported being motivated to participate in programs of social benefit and to take opportunities to learn new skills (Craig et al., 2021).

DISCUSSION

This scoping review found 29 citizen science programs operating across 16 countries, and three of these programs showed wide geographic coverage. Citizen science has been explored as a tool to monitor native and exotic mosquitoes, and the programs have used different approaches, including traps, smartphone apps, questionnaires, and partnership with local volunteers that inspect mosquito breeding sites in their neighbourhoods. Overall, these programs have demonstrated capacity to upscale data collection and to connect citizens to researchers and public health authorities.

Almost all the programs reported being free to join and allowing open communication before, during, and after trials. Also, programs such as Mosquito Alert and Muckenatlas, which have been running for almost ten years, have maintained an active cohort of citizen scientists that keep contributing over time. The Mozzie Monitors program has proven effective to collect mosquitoes of medical and ecological importance and has provided monthly feedback to participants through a free-to-use online platform.

The World Health Organisation (WHO) has set goals to tackle vector mosquitoes worldwide and to reduce mosquito-borne infections by at least 60% by 2030. This plan, named Global Vector Control, was established in 2016 and focuses on four main pillars: strengthening inter- and intra-sectoral action and collaboration; engaging and mobilizing communities; enhancing vector surveillance, and monitoring and evaluating interventions; and scaling up and integrating tools and approaches (WHO 2017). These four pillars support the development of sustainable vector control implementations.

Programs that seek partnerships with stakeholders in different sectors are aligned with the first of the WHO's fundamental pillars to tackle mosquito-borne diseases worldwide. All programs identified through articles included in this scoping review align with the second of the WHO's pillars of effective vector control; as community engagement and mobilisation are the core of this pillar, every citizen science approach described here meets this requirement. The sustainability of the programs aligns with the third pillar set by WHO; to ensure these programs are sustainable, it is necessary to evaluate the programs' long-term benefits and possible educational gains. Finally, the last pillar proposes that programs should develop methods that are appropriate to the local settings. To meet this concern, strategies of mosquito monitoring must be accessible to the broad community. Programs that rely on participants owning technological devices (such as smartphones and internet connection) could face some challenges in impoverished areas.

While there is great potential to assist local health authorities, citizen science mosquito surveillance initiatives also face many challenges in ensuring outcomes are translatable to improved public health policy and practice. Despite being a relatively new field of study, these programs have been increasing owing to the concern regarding the emergence and re-emergence of mosquito-borne infectious diseases (Palmer et al. 2017). Citizen science may prove critical in detecting exotic species and disease vectors, demonstrating that this partnership is a powerful tool to be used in mosquito surveillance programs worldwide, as it allows highly geographically refined data collection.

CONCLUSIONS

The included citizen science programs focused on different strategies and methods according to their local and national contextual needs. Most of the programs reported being free or low cost, and were designed so that participants required no specialist technical expertise. Also, citizen scientists valued the opportunity to actively contribute to a scientific activity in which they saw value.

Citizen science mosquito surveillance programs have proven successful both locally and nationally to yield information on mosquito abundance, diversity, distribution, and nuisance. Programs have been using different methods to address specific aims, and some projects have contributed to unexpected findings, such as the detection of exotic species. The programs listed in this global review could establish a long-term citizen science culture on mosquito surveillance through a hands-on approach, besides bringing additional information to formal mosquito surveillance programs. Partnerships with government departments could benefit researchers, databases, public health agents, and the broad public. They could also be used as early warning systems to predict mosquito-borne diseases risks or outbreaks in areas where some diseases are endemic.

Additionally, programs using low-cost technologies have the potential to upscale existing mosquito surveillance. However, the integration of such successful methods with the assistance and representativeness of local partners, such as village volunteers or local community leaders, could provide an opportunity to grow citizen science mosquito monitoring interventions in impoverished areas with low access to technology or low internet coverage.

Notwithstanding these potential advantages, the role of citizen science mosquito surveillance in informing disease management directly remains unclear. Ensuring that citizen science methods yielded robust metrics that could be used as triggers for vector control should be a priority for research.

Establishing a citizen science culture in mosquito surveillance through a hands-on approach is essential and aligns with the Vector Control Response pillars outlined by WHO. Although the WHO does not mention the term citizen science in its Global Vector Control Response, the 64-page document developed in partnership with global experts in mosquito monitoring and neglected diseases highlights the importance of effective community engagement and mobilisation in vector control. Further, better coordination within and between sectors and novel interventions with proven effectiveness are among the response's main purposes. Citizen science frameworks on mosquito surveillance could have the potential to address the goals and targets set by the WHO.

FUTURE ACTIONS

There is a demand for citizen science initiatives on mosquito management. This demand is supported by the WHO and numerous local initiatives that we found in the first screening of this scoping review. Also, numerous studies have been reported in African countries, presenting frameworks to establish citizen science approaches to address the challenges related to mosquito management in the future (Asingizwe et al. 2018; Ashepet et al. 2021).

Further research is necessary to address the logistical issues in establishing sustainable programs running in partnership with government agencies and public health authorities. Also, additional studies focusing on transdisciplinary approaches are needed to assess how increased data on mosquito populations through citizen science can be translatable to improved public health policy and practice. For example, researchers in Australia are running a trial named Mozzie Month. This is the first national trial of the Mozzie Monitors program in the country, and aims to answers questions about feasibility, sustainability, biosecurity, ownership, and governance. The trial expects to further investigate how integration of citizen science–derived data and professional surveillance are achieved.

The need to expand projects involving public participation in mosquito- and mosquito-borne disease–related studies is evident. Enhancing community engagement and mobilisation in mosquito monitoring through citizen science could be a tool to tackle mosquito-borne diseases in increasingly sustainable and long-term ways.

SUPPLEMENTARY FILES

The Supplementary Files for this article can be found as follows:

- **Supplemental File 1: Appendix 1.** Search strategy. DOI: *https://doi.org/10.5334/cstp.469.s1*
- **Supplemental File 2: Appendix 2.** Current research published on citizen science mosquito surveillance. DOI: *https://doi.org/10.5334/cstp.469.s2*
- **Supplemental File 3: Appendix 3.** Approaches and strategies used by citizen science mosquito surveillance programs worldwide. DOI: *https://doi.org/10.5334/cstp.469.s3*

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COMPETING INTERESTS

The authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

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