Madeira Mosquito Surveillance App (MMSA): Leveraging Mobile Phone Apps for Enhanced Mosquito Surveillance

Aisha Aldosery
UCL Centre for Digital Public Health in Emergencies (dPHE)
University College London
London, United Kingdom
a.aldosery@ucl.ac. com

Anwar Musah
UCL Department of Geography
Geospatial Analytics and Computing University College London
London, United Kingdom
a.musah@ucl.ac.uk

Bruna Ornelas de Gouveia
ITI – LARSyS; Regional Health
Directorate – Secretariat of Health and Civil Protection
Funchal, Portugal
bruna.gouveia@madeira.gov.pt

Patty Kostkova
UCL Centre for Digital Public Health in Emergencies (dPHE)
University College London)
London, United Kingdom
p.kostkova@ucl.ac.uk

***Abstract*—Mosquito surveillance is crucial for understanding the dynamics of mosquito populations, the implementation of public health programme aimed at controlling and preventing the spread of mosquito-borne diseases such as zika, chikungunya and dengue. Environmental surveillance agents, tasked with conducting routine entomological surveys in regions burdened with infective mosquitoes play an essential role in vector surveillance. Digital intervention, through mobile phone technology, offers the potential to augment mosquito surveillance efforts by overcoming the limitations inherent in traditional paper-based data collection methods. This public health informatics study introduces a multi-profile mobile application designed to enhance the process of data collection from mosquito ovitraps, ensure timely reporting, and improve field worker performance in Madeira Island, with an emphasis on user-centered design. The application seeks to boost operational efficiency for field agents and to streamline decision-making processes for health authorities. It explores the technical design, user experience, and architecture, alongside the challenges faced during implementation, including logistical hurdles during adaptation. Crucially, this research considers the varied on-ground challenges encountered by agents, such as fears of data loss or errors in entry, which add complexity to the digital transition. The transition to a digitised data collection system is poised to have a significant impact which could facilitate the timely use of predictive analytical models to forecast mosquito population dynamics, enabling the early detection of hotspots. This, in turn, would allow fieldworker agents to be alerted to immediate action and direct their efforts to high-risk areas, significantly improving the efficiency of interventions against mosquito-borne diseases.**

Keywords*— *digital intervention, mobile application, real-time, mosquito surveillance, ovitraps.

I. Introduction

Mosquito-borne diseases impose a significant public health burden on inhabitants of tropical regions, such as Latin American countries, and the outermost ‘autonomous’ regions for Portugal, like Madeira Island. Due to the ideal environmental and climatic conditions, Aedes aegypti (*Ae. aegypti*) was previously present in Europe until the mid-20th century and has been re-established in Madeira and the Black Sea region. In the Portuguese island of Madeira, *Ae. aegypti* was first reported in 2005, in Funchal city. Since then, this mosquito has expanded its distribution throughout the southern coast of the island. The presence of this mosquito on the island, coupled with the introduction of DENV-1, led to an outbreak of dengue fever, with more than 2,000 notified cases between October 2012 and March 2013. The epidemic prompted the reinforcement of vector control activities on the island in the subsequent months, particularly in the more densely populated area of Funchal city [1], [2].

Mosquito control surveillance is a critical component of health interventions initiated by governmental public health agencies and authorities to control and prevent the spread of diseases. Environmental surveillance agents play an indispensable role in mosquito management by identifying and managing positive ovitraps during scheduling routine visits. During these visits, the agents record data on paper forms designed by the local health authority. Despite the success of the agents in mosquito control surveillance, the traditional paper-based system and the process of transcribing data onto a computer system are time-consuming and error-prone tasks. These practices potentially yield low-quality data and cause delays in analysis. Consequently, using mobile phone technology is considered as a more effective method to support health agents in collecting and reporting data in real time [3].

Mobile applications deliver high-quality, real-time field data and enhance the coordination and performance of surveillance agents [3] thereby representing a promising tool in the fight against mosquito-borne diseases. In response to this challenge and guided by the recommendations of local environmental agency and the health authority on Madeira Island, we have developed a digital intervention tool, a mobile phone application. This tool improves the surveillance of mosquitoes by providing timely and geolocated reports on the presence and absence of mosquitoes (eggs or larvae) in ovitraps distributed across the island. Where possible, it also collects relevant climate data, such as air temperature and humidity.

The work detailed in this paper outlines the comprehensive process of co-designing, architecting, and co-development of the multi-profile Madeira Mosquito Surveillance Application (MMSA), emphasizing a user-centric approach at every stage. This application, pivotal for environmental surveillance agents on Madeira Island, was developed through a collaborative, iterative process that prioritised the needs, preferences, and feedback of the end-users, ensuring the final product was not only functional but also intuitive and tailored to enhance their routine inspection visits. By delving into the intricate steps involved in the app's creation—from conceptualisation to deployment—and highlighting the primary challenges and limitations encountered, including technical and logistical hurdles, this study serves a dual purpose. It sheds light on the specifics of the project at hand, offering a holistic view of the digital intervention tool's implementation and adoption on the ground, and simultaneously acts as a comprehensive blueprint for researchers and practitioners aiming to incorporate mobile phone technologies into the realm of scientific investigation.

The detailed examination of these aspects, underscored by a steadfast commitment to a user-centric design philosophy, provides valuable insights and guidelines that can be adapted and applied across a wide array of scientific disciplines seeking to leverage mobile technology for enhanced data collection, analysis, and intervention strategies. This paper presents the development and deployment of a specific technological solution as well as highlights how aligning technology design with user needs is crucial for the effective implementation and acceptance of digital tools in scientific research.

The paper is organised into eight primary sections for clarity and depth of exploration. Section I introduces the research context and objectives. Section II reviews existing works on mosquito surveillance technologies. Section III an overview of the study area and regional settings, along with mosquito surveillance strategies in Madeira. In Section IV, the pre-development and user engagement process is outlined, highlighting the participatory design approach. Section V, dives into the technical system's architecture, technology choices, and user interface design of the MMSA. Section VI outlines the app's core functionalities and distinguishing feature. Section VII discusses the project's outcomes, encapsulating lessons learned and future expansion potential. The final section, Section VIII, concludes with key takeaways and the impact of MMSA on public health and mosquito surveillance in Madeira.

II. Related works

The integration of mobile technologies into public health research, particularly for mosquito-borne disease surveillance, represents a significant evolution from traditional methods. By leveraging digital solutions for both disease and vector monitoring, these applications have not only transformed conventional surveillance strategies but also facilitated a more efficient data capture and transfer process, marking a critical shift towards the adoption of technology in enhancing disease control efforts [3]. Yet, the digital surveillance is identified as one of the major challenges in digital public health [4].

MEWAR [5] and Chaak [6] represent significant advancements in utilising mobile applications and web dashboards for real-time mosquito surveillance. MEWAR, with its focus on bridging field data collection and centralised data analysis in Northeast Brazil at the property survey level, mirrors MMSA's objective, which aims to streamline surveillance processes with targeting both households and public areas in Madeira. Conversely, Chaak improves data transcription accuracy and operational efficiency in Mexico by digitising the collection of immature mosquito stages, yet the system also suffers from incompatibility with various mobile operating systems and is unsuitable for large-scale implementation. Both projects underscore the utility of mobile applications in facilitating data collection but differ in their geographic and operational focus compared to MMSA.

GMOD [7], Mosquito Alert [8], and iNaturalist [9] projects exemplify the power of citizen science in mosquito surveillance. These platforms engage the community in identifying and reporting mosquito habitats, thereby supplementing traditional surveillance mechanisms. Unlike MMSA, which is designed to support environmental surveillance agents directly, these initiatives expand the scope of surveillance by harnessing public participation. This comparison highlights the diverse strategies in digital surveillance, MMSA's agent-focused approach versus the broader, community-engaged (i.e., Citizen Science). Other project such as VazaDengue [10] introduces an innovative use of social networks to combat mosquito-borne diseases, emphasizing community engagement and the dissemination of actionable information. While VazaDengue focuses on leveraging public reports for preventive measures, MMSA concentrates on enhancing the efficiency of environmental surveillance agents through a dedicated mobile app. This contrast underscores the varied applications of digital tools in mosquito surveillance, from public health communication to specialised data collection.

In summary, the transition towards digital interventions in mosquito surveillance, reflects a growing recognition of the technology's potential to augment traditional vector control strategies. The MMSA, with its focus on user-centric (i.e., agent-centric) data collection design, contributes to this evolving landscape by addressing the specific needs of Madeira Island's mosquito surveillance efforts. Each project, while unique in its approach and objectives, collectively underscores the transformative impact of digital technologies in enhancing.

III. Area and Mosquito Surveillance Strategies in Madeira

Madeira Island, located in the North Atlantic Ocean, features a distinctive ecological landscape marked by its varied ecology and micro-climates, elements that are highly pertinent to the study of mosquito-borne diseases. The island's temperate climate, coupled with its socio-economic links to areas where vector-borne diseases are widespread, underlines the essential need for diligent mosquito surveillance.

Following the dengue outbreak in 2012, Madeira enhanced its vector control strategies significantly. The mosquito surveillance programme across Madeira Island is now comprehensive, incorporating a diverse range of strategies to monitor and manage mosquito populations. This was achieved by establishing an island-wide network of ovitraps and adult traps, marking a pivotal enhancement in the island's extensive vector control efforts. This initiative has evolved into a critical element of Madeira's elaborate vector control programme, which integrates community-based strategies with sophisticated surveillance systems. The programme predominantly utilises two methods: deploying

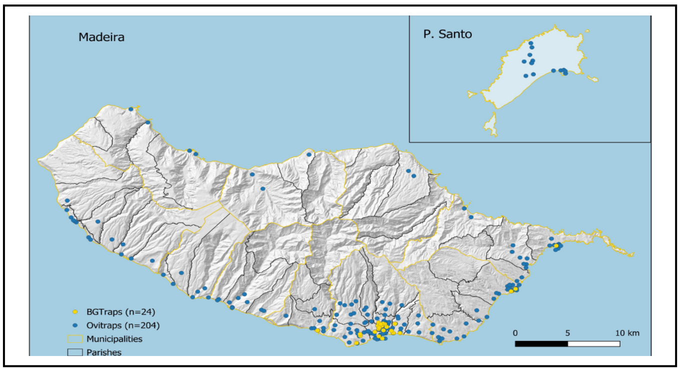

Fig. 1. The distribution of mosquito ovitraps and adult traps across the island

specific traps for adult mosquitoes and ovitraps for monitoring the immature stages of the mosquito population [2].

The network of ovitraps, comprising 204 units distributed across Madeira Island and extending to Porto Santo, is instrumental in gauging mosquito densities and curbing their proliferation by monitoring immature stages (i.e., eggs and larval) (Fig.1). This surveillance strategy is methodologically robust, leveraging the strategic deployment of ovitraps to monitor and control mosquito populations effectively. Each ovitrap, consists of a black plastic bucket fitted with bands of red velvet-paper for egg deposition and containing approximately 1.5 litres of tap water, is inspected weekly (Fig.2). During these inspections, the egg-laden paper and water are replaced, and the eggs are subsequently counted under a microscope. This process yields invaluable data for analysing mosquito breeding trends and population dynamics, thereby enhancing our understanding of vector behaviour and informing control measures [11], [12].

The BG-Sentinel trap, recognised as the pre-eminent tool for the monitoring of adult mosquitoes, boasts approximately 24 units (Fig.1) strategically placed across Madeira Island. Its compatibility with a diverse array of mosquito attractants enhances its versatility, making it an indispensable asset for both research and surveillance efforts in the domain of mosquito control. A distinctive benefit of this trap is its ability to keep mosquitoes alive, thus enabling the detection of virological or RNA-based arboviruses with greater efficacy. However, a notable drawback is its dependence on a continuous supply of electrical power [13] (Fig. 2). Despite this, the BG-Sentinel trap is celebrated for its environmentally friendly approach to reducing *Ae. aegypti* populations thereby circumventing the need for chemical insecticides and contributing to sustainable vector management practices [14].

Fig. 2. Ovitrap (left image), a BG-Sentinel trap (right image) and red-paper with some stick eggs (middle image)

The networks of both ovitraps and BG-Sentinel traps are currently operational and play a pivotal role in the weekly collection of data for mosquito surveillance on Madeira Island. This dual methodology facilitates comprehensive surveillance of both adult and immature stages of mosquito populations, which is critical for the effective control and management of these vectors. The Regional Directorate of Health in Madeira manages the distribution and supervision of traps and ovitraps, assigning environmental agents to designated areas for consistent monitoring. This intricate surveillance programme, customised to the island's diverse climatic and geographical contexts, is essential for effective mosquito population control and the mitigation of disease transmission.

In this research, the primary focus is on harnessing the data and insights from ovitraps mosquito surveillance methods by working closely with the environmental agents using user-centred design for the development of the surveillance app. This approach ensures that the application is not only informed by real-world scenarios but is also fine-tuned to meet the specific challenges and requirements identified through the comprehensive surveillance program in Madeira. By integrating this empirical data, the app is poised to offer targeted solutions, enhancing the efficacy and impact of Madeira's mosquito control efforts.

IV. Pre-Development and Initial User Engagement

A. *Requirements Gathering*

Prior to the initiation of the mobile phone application's design and development, it was essential to acquire a thorough understanding of the existing mosquito surveillance methodologies employed in Madeira from the environmental agents to ensure a user-centred approach was followed throughout. This initial phase entailed the dissemination of detailed data to the research team, encompassing insights into mosquito ovitraps, geographic information on municipalities and parishes across the island, and the paper-based surveillance forms used in the field. This preparatory stage was crucial for acquainting the team with the current surveillance strategies and techniques that are relevant to the unique context of Madeira.

Three distinct forms were provided, each offering unique insights into mosquito surveillance and reporting forms: **Regional Surveillance Form:** Widely used across Madeira and mainland Portugal, this form provided a broad spectrum of data, which covers information about both adult and immature mosquitoes and other essential details that enhances our understanding of mosquito populations and its abundance. **Immature Mosquitoes Form:** Focused on immature mosquito data collection, this form included details on collection sites, habitats, and methods, offering insights into breeding habits and distribution patterns. **Adult Mosquitoes Form:** Targeting adult mosquito surveillance, this form contained details on collection specifics, habitat types, environmental conditions during collection, and additional observational notes. This form was key to understanding the behaviour and distribution of adult mosquitoes in different habitats.

All information was translated into English and organised into an Excel sheet, ready for review by the local team in Madeira. This translation and reorganisation into a user-friendly format were instrumental in offering a comprehensive overview of current practices, crucially informing the app’s design and development stages.

B. User Experience: Mock-up Development using Figma

Following the initial data gathering and analysis phase, the development process progressed to creating mock-ups of the surveillance app using Figma[1]. This collaborative interface design tool played a crucial role in visualising theoretical concepts and creating prototypes for stakeholder and developer review. This stage was instrumental in converting abstract ideas into tangible designs, providing an interactive platform for environmental agents to offer feedback. The use of Figma for mock-up creation bridged the gap between conceptualisation and practical implementation effectively. The initiation of mock-up development for the app, with information gathered from Madeira team, was expedited by the insights and expertise acquired during the creation of a similar mobile phone surveillance app we authored and tailored for Brazil [5]. Despite differences in surveillance strategies between the two settings, the foundational knowledge acquired was pivotal in guiding the initial design process for Madeira surveillance app, allowing for a head start in the mock-up creation using Figma.

C. Inaugural Workshop

The inaugural workshop, held on the 24th of May 2022, signified a pivotal moment in the development of the application. Environmental agents were presented with the initial mock-ups, facilitating an interactive evaluation, and enabling them to impart their critical insights and recommendations. This session was instrumental in refining the app's design direction, with agents distinguishing the pertinent information for Madeira from that primarily intended for the mainland, as derived from the three forms provided. Furthermore, the workshop showed the diverse roles of the agents, thereby delineating user access control within the app to ensure tailored functionality for each role.

Furthermore, the workshop showcased the app's capacity to optimise field operations, informed by the Brazilian project's learnings. The agents, through engagement with both Brazilian instances [5] and the Madeiran prototype, enacted a range of field scenarios, critically assessing the required actions. This collaborative exercise was immensely productive, offering deep insights into Madeira's unique environmental conditions and the app's practical application in such settings.

D. Subsequent Workshop

The second workshop, conducted on 22 September 2022, sought to capitalise on the feedback and insights acquired from the initial session. This workshop marked the transition from theoretical design to practical application, with environmental agents engaging directly with a developed version of the app on their mobile devices. The hands-on testing allowed for a more nuanced critique, with agents executing a series of structured scenarios. These included tasks such as new user registration, property and ovitraps management - each designed to rigorously evaluate the app's functionality.

Fig. 3. Workshop with Environmental Agents, Madeira, 2022

The feedback obtained during the workshop was comprehensive, addressing several facets of the application's usability. Notably, non-technical users highlighted the need for an integrated help feature within the app to assist in navigation, as opposed to a separate manual. Additionally, there were comments on technical compatibility challenges, particularly with older Android devices. Suggestions also included implementing manual data entry option for GPS coordinates and visual indicators to distinguish between active and deactivated traps. Moreover, the proposal to include specific data fields for monitoring infected larvae and pupae by the lab users aimed to enhance the app's data collection efficiency. Overall, the reception of the app was positive, with the issues raised being classified as minor.

V. System Architecture and Technology Stack

The development of the mobile app leverages a sophisticated system architecture combining Ionic-React with TypeScript for the frontend and Node.js with ExpressJS for the backend, alongside MongoDB Atlas for data storage. This intervention tool is designed to fulfil the essential requirements of mosquito surveillance in Madeira Island.

Client-Side: The client-side of the system, serving as the interactive user interface, integrates seamlessly with the server-side via API calls. Developed in Ionic, Ionic's cross-platform capability enables a unified codebase for Android and iOS, chosen for its efficiency in compiling JavaScript, including React used here, into native applications. The application supports a diverse user base including environmental agents, lab users, and administrative personnel, each with distinct roles and access privileges. Given the varied user roles, the app facilitates specific functionalities: digital form submissions for environmental agents conducting routine ovitrap surveillance, data entry for lab users analysing water samples, and ovitrap management capabilities for administrators. The app also supports the use of GPS for capturing spatial data essential for field surveillance activities.

The mobile application requires a smartphone or tablet with Android or iOS support and network access (WiFi or GSM). Development and testing predominantly used Android due to simpler access to Android Package Kit (APKs) - is a file format used by the Android operating system for the distribution and installation of mobile apps and middleware - and less stringent requirements than Apple's ecosystem. This pragmatic approach ensures broader accessibility and compatibility, aligning with the project's user base needs.

Server-Side: The backend architecture is constructed using Node.js, selected for its non-blocking I/O model which ensures efficient processing of HTTPS requests and user authentication. ExpressJS, a minimalist web framework for Node.js, defines the API endpoints, facilitating streamlined communication with the database. Hosted on Heroku, the server benefits from cloud scalability and reliability.

[1] https://www.figma.com/

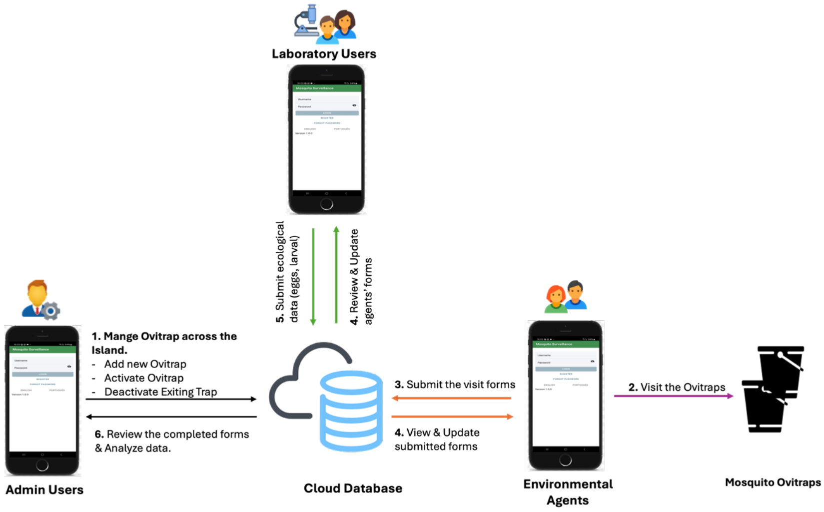

Fig. 4. Overview of the Proposed MMSA System

MongoDB Atlas, a cloud-based NoSQL database, is chosen for its schema-less nature, allowing for flexible data modelling which is essential given the variability in surveillance data and forms within time and location.

Database Configuration: The database configuration was aligned with the ovitrap data, demonstrating the system's dedication to granularity and accuracy. This alignment involved transforming the ovitrap data, provided by Madeira's local health authorities, into JavaScript Object Notation (JSON) for effective database integration. However, the configuration purposely omits direct incorporation of property addresses, adhering to local surveillance practices that typically do not involve property visits unless specified under certain conditions. The potential use of the Google Geolocation API is identified as a means to augment data entry. Furthermore, the integration of the Mongoose library plays a pivotal role in enhancing data relationship management and maintaining data integrity, thereby bolstering the system's robustness, and ensuring the precision of the surveillance initiatives. This approach underscores the importance of sophisticated data handling in supporting the system's overarching goals.

Security Measures: To safeguard the system, a token-based authentication mechanism is employed, utilising JSON Web Tokens (JWT) to secure API endpoints. This ensures that users access only data relevant to their roles, maintaining data confidentiality and integrity. Additionally, the system restricts access to users with an official government email address, further enhancing security by ensuring only authorised personnel can use the system. This design emphasises the protection of sensitive information, adhering to best practices in cybersecurity [15].

System Testing Strategy: In the development of the mobile application for mosquito surveillance in Madeira, a comprehensive system testing strategy plays a pivotal role in ensuring the application's reliability and usability. The backend system undergoes rigorous unit testing using the Mocha and Chai frameworks, chosen for their versatility and ease of integration into the Node.js environment. These tools facilitate the creation and execution of tests that verify the correctness of individual units of code, essential for early detection of potential issues.Continuous Integration (CI) and Continuous Deployment (CD) practices are integral to the development workflow, with CircleCI employed to automate the testing processes. Before any integration into production, CircleCI orchestrates a series of automated tests and deployment procedures, ensuring that only thoroughly vetted code is released. This approach minimises the risk of errors and enhances the overall quality of the application.

While the backend benefits from established testing routines, the frontend testing framework is still in the planning stages. Future development phases will see the introduction of Storybook and Selenium for frontend testing. Storybook will be utilised for developing and testing UI components in isolation, thereby speeding up the frontend development process and ensuring component integrity. Selenium, an automation testing framework, will be employed to simulate user interactions across various browsers, verifying the application's functionality and user experience in real-world scenarios.

The combination of these testing tools and methodologies underscores a commitment to delivering a robust, user-friendly application. By embracing both unit testing for the backend and planning comprehensive testing for the frontend, the project aims to set a high standard for application reliability and user satisfaction. This comprehensive system architecture and technology stack underpin the mobile app's functionality and iterative feedback workshops with the end users ensured it meets the specific needs of mosquito surveillance in Madeira. Through careful selection of technologies and frameworks, the project aims to deliver an efficient, secure, and user-centric solution for mosquito control efforts.

VI. App Features and Functionalities

Fig. 4 presents an overview of the proposed system and the interaction between the multi-users and the system. In this section, we detail the key functionality and the features of the system.

A. User Role-Specific Features

Within the architecture of the system, a hierarchical structuring of user roles ensures a streamlined operation of mosquito surveillance activities, the MMSA supported three main users.

At the pinnacle of this hierarchy are the administrative users, affiliated with the Regional Health Directorate of the Autonomous Region of Madeira. These individuals wield comprehensive oversight over the ovitrap distribution network, exercising responsibilities that encompass the (1) deploying new traps, (2) activating and deactivating units based on operational assessments and physical condition evaluations (Fig. 5), and (3) monitoring progress through form filtering by user and visit location, whether an ovitrap or property.

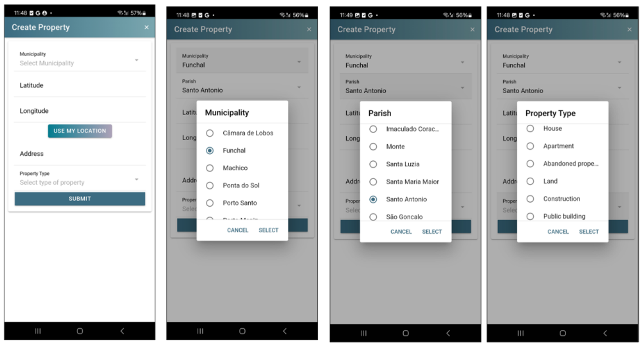

Fig. 5. Agent User: Creating Property.

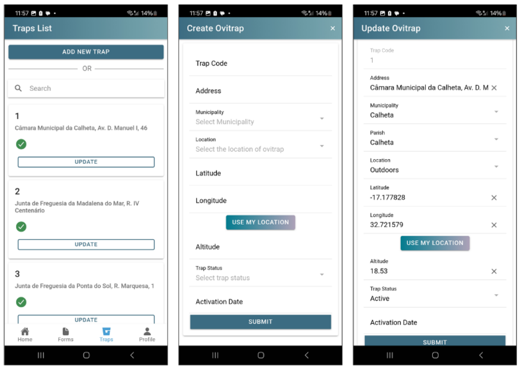

Fig. 6. Administrative Users: Adding, Updating, and Deactivating the Ovitrap List.

Sequentially, the environmental agents form the operational core, undertaking field visits for data collection. Their system access is meticulously tailored to ensure they can submit and review only their data entries, thus upholding the integrity and confidentiality of surveillance information. Under certain conditions, for example when public report a hotspot, agents may visit properties for surveillance and can input property address information, with the system retaining this data for future reference. Agents' capabilities include (1) filling out forms at ovitrap sites (Fig. 6), (2) viewing and updating their forms, (3) adding property information, and (4) conducting property visits (Fig. 7).

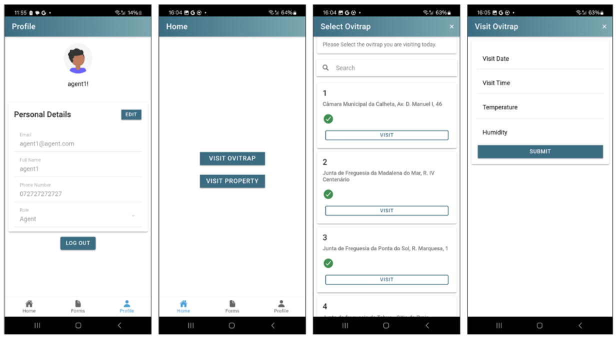

Fig. 7. Agent Users: Agent Profile, Ovitrap Selection and Visiting Form.

Completing this triad, lab users engage in the analytical phase, examining water samples procured by environmental agents. Their role extends to augmenting the initial data with detailed analyses, including egg and larva counts by updating the same form filled-out by the agents with information collected from the water sample (Fig. 7). Given the collaborative nature of their work with administrative users, lab users are granted access comparable to that of the administrators, facilitating a seamless integration of field data with laboratory findings. Lab users are granted comprehensive access, mirroring the functionalities available to both administrative and agent users.

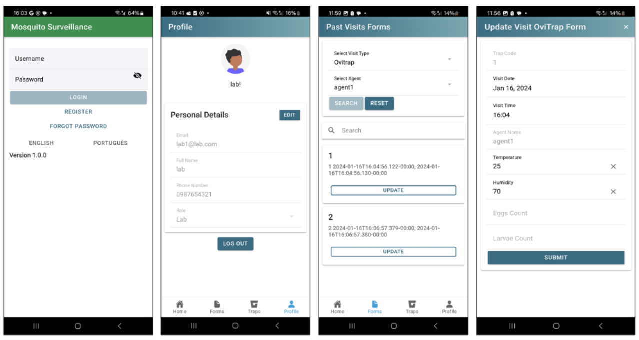

Fig. 8. Lab Users: Home page, Lab User Profile, Monitoring Past Visits and Updating Them with Egg and Larval Counts.

This delineated access framework underscores the system's methodical approach to data collection, analysis, and management, pivotal for the efficacious monitoring and control of mosquito populations.

B. Data Collection Mechanisms

In the domain of mosquito surveillance facilitated by the developed mobile application, the incorporation of location tagging, and real-time data submission emerges as a pivotal innovation. This digital methodology significantly streamlines the data collection process for environmental agents by furnishing precise, geographically tagged locations, thereby ensuring the accuracy of surveillance data. The application's capacity for real-time submission constitutes a marked advancement over conventional paper-based systems, effectively curtailing the latency between data collection and its accessibility to health authorities. This immediacy of data provision enables a dynamic adaptation of surveillance models, transitioning from a weekly to a real-time analysis framework [16].

C. Usability and Accessibility

The mobile application's commitment to usability and accessibility is manifest in its support for English and Portuguese, broadening its appeal and utility across diverse user demographics. The implementation of a user interface, informed by extensive user experience studies [17], significantly enhances its usability. This user-centric design approach, which encompasses everything from the colour scheme to the simplicity of the workflow, ensures that the application is not only functional but also intuitively aligned with the users' needs and preferences.

VII. Discussion And Future Work

Within the context of surveillance on Madeira Island, several critical technical considerations have emerged, particularly in relation to device compatibility. A significant challenge has been compatibility issues with older Android devices, often stemming from the rapid advancements in mobile phone operating systems that outpace the hardware capabilities of earlier models. The application, developed using the contemporary Ionic-React framework, is designed to leverage advanced features and APIs that may not be supported by older versions of Android. Consequently, these devices may lack the requisite processing power, memory, or system functionalities essential for efficiently running newer applications. Furthermore, security protocols and software dependencies undergo frequent updates, necessitating the use of more recent hardware to achieve optimal application performance. This scenario could lead to the application failing to install or operate correctly on such devices.

It's important to note that while Ionic-React facilitates cross-platform development, enabling potential deployment on both Android and iOS, this version of the application has been exclusively exported and tested on Android devices. This decision was informed by the prevalent use of Android among the target user base on Madeira Island, as well as the fact that government-issued tablets and phones, which are extensively used by environmental surveillance agents, are all Android-based. Consequently, although the app's underlying technology supports cross-platform functionality, its current implementation and testing have been Android-specific, primarily due to the platform preferences and available hardware within the intended user community.

The current version of the application, focusing on optimising data capture and dissemination, lacks photo capture/uploads and report import/export functionalities. This strategic emphasis enhances the effectiveness and responsiveness of mosquito surveillance operations. Efficiency in data collection is assessed by the speed, accuracy, and reduction in manual errors. Integrating these functionalities could significantly improve user experience and confidence, especially for field agents. Uploading photos would allow for more detailed and verifiable records of mosquito breeding sites and ovitrap conditions, thereby improving data quality and providing evidence to support surveillance efforts. Likewise, enabling report exportation would aid in the efficient sharing and analysis of collected data.

The absence of offline functionality in the current iteration, due to consistent network coverage where ovitraps are deployed, will be addressed by planned enhancements like caching to support data collection in areas with intermittent connectivity.

Currently, we utilise GPS data from Android devices via Capacitor’s Geolocation API, which, despite its reliability, includes typical GPS inaccuracies. We chose this method for its simplicity and balance of project needs and resources. However, we acknowledge its spatial accuracy limitations. To enhance precision in future iterations, we are considering advanced technologies like the Google Geolocation API, which utilises multiple sources to refine location data, or algorithms that average GPS readings to minimise anomalies, thereby improving the effectiveness of our surveillance initiatives.

The incorporation of such additional features would significantly enhance future versions of the system. These tools would not only facilitate administrative oversight but also optimise resource allocation for ovitrap distribution, thereby enhancing the efficacy of mosquito surveillance efforts on the island.

The integration of digital tools for field agents, particularly in the context of mosquito surveillance, encounters distinct challenges that vary by region. In Madeira, agents frequently express fear that transitioning to digital platforms may lead to errors and potential data loss, which could prevent them from substantiating the completion of their tasks. This fear extends to the use of smartphones and applications, with concerns that any malfunction could compromise their work. Consequently, many agents emphasise a preference for redundant data entry, using both digital and traditional paper methods to secure their records. However, in other regions such as Brazil [5], the hesitancy to embrace digital solutions is compounded by additional factors. Field agents express a pronounced fear of physical loss of the devices themselves, as well as the unreliable network coverage that plagues many areas of the country. This fear is not unfounded, as the loss of a device could mean a significant loss of data and work progress, adding an extra layer of risk to their daily tasks.

Therefore, the provision of capacity building training workshops supported with detailed manuals is essential. Training should be hands-on and context-specific, empowering agents to utilise digital tools effectively regardless of external challenges. Moreover, ongoing support and open communication channels between agents and the implementing bodies can create a feedback loop for continuous improvement of the digital tools and the training programs themselves. These measures, taken together, can facilitate a smoother transition to digital interventions in diverse settings, addressing the unique challenges encountered in each region.

Digitising data collection processes marks a significant shift from paper-based methods, introducing real-time data submission that streamlines surveillance activities. This shift eliminates the need for physical document transfer and allows for immediate data analysis, particularly when integrated with other digital systems [12], [13]. The outcome is an increased speed and precision in public health responses to mosquito-borne disease threats.

The innovation inherent in this digital tool is its enhancement of public health through the optimisation of surveillance operations. It provides quick data collection and dissemination, improving the response of health authorities to vector-borne diseases.

Incorporating a user-centred design philosophy with a focus on interface and workflow simplification, integrating

GPS functionality and tailored linguistic adaptations, the application stands established as a paragon of user-centric innovation in public health technology.

Looking ahead, the insights gleaned from the deployment of this intervention in Madeira offer a foundational blueprint for the customisation of digital surveillance tools across diverse regional landscapes. Investigating the tool's relevance and adaptability in regions confronted with unique surveillance challenges, such as those in Latin America and Asian countries with endemic mosquito populations, could further underscore its utility and versatility. This exploration holds the potential to revolutionise public health strategies within a multitude of global contexts, thereby extending the impact of this innovative approach to mosquito surveillance.

VIII. Conclusion

The transition to a digital surveillance tool, as discussed in this study, marks a pivotal advancement in the public health domain, particularly in combating mosquito-borne diseases. The application's capacity for providing real-time, actionable data heralds a paradigm shifts in health authorities' operations, fundamentally redefining disease prevention and vector control strategies. This research presents the significant influence digital innovation can have on improving community health outcomes and fostering public engagement. As a scalable and versatile solution, the digital tool establishes a new standard for vector surveillance and could serves as a global model in the fight against infectious diseases. Mobile technology has enabled significant advances in mosquito control, transitioning from outdated paper-based systems to sophisticated digital platforms.

This paper delineates the process of designing, developing, and testing the mosquito surveillance system, highlighting its potential to strengthen entomological surveillance against mosquitoes transmitting several lethal arboviruses. The system offers crucial functions, enabling workflow tracking via a mobile app and delivering real-time geolocated data. It also serves as a tool for the integration and refinement mosquito surveillance models at a granular level. Adhering to rigorous software design and development practices, the system's architecture has been crafted to enhance its quality and reduce maintenance requirements.

While the system tailored for environmental surveillance agents in Madeira, reflecting the locale's context, its scalability ensures it could be adapted globally. The insights gained from the developmental process are poised to be transferable to other intervention tools, offering a wealth of knowledge for broader application. The system's potential for integration into existing government public health programmes that utilise digital interventions highlights its adaptability and the transformative prospects it holds for enhancing global health infrastructure.

Acknowledgment

Special thanks to Duarte Nuno Gouveia Araujo, José Maurício Faria Santos, Bela Viveiros, Guilherme Madruga, and The Regional Health Directorate of the Autonomous Region of Madeira for their invaluable contributions to the MMSA system design and fieldwork support. This research was funded by the Belmont Forum and supported in the UK by UKRI NERC under grant NE/T013664/1. The PhD studentship of the lead author was sponsored by King Abdulaziz City for Science and Technology (KACST), Riyadh, Saudi Arabia.

References

[1] G. Seixas *et al.*, "Origin and expansion of the mosquito Aedes aegypti in Madeira Island (Portugal)," *Scientific Reports 2019 9:1*, vol. 9, no. 1, pp. 1–13, Feb. 2019, doi: 10.1038/s41598-018-38373-x.

[2] S. C. Margarita YS, Grácio AJ, Lencastre I, Silva AC, Novo MT, "First record of Aedes (Stegomyia) aegypti (Linnaeus, 1762)(Diptera, Culicidae) in Madeira Island-Portugal.," *Acta Parasitol Port (Acta Parasitológica Portuguesa)*, vol. 13, pp. 59–61, 2006.

[3] M. A. Carrillo, A. Kroeger, R. Cardenas Sanchez, S. Diaz Monsalve, and S. Runge-Ranzinger, "The use of mobile phones for the prevention and control of arboviral diseases: a scoping review," *BMC Public Health*, vol. 21, no. 1, pp. 1–16, Dec. 2021, doi: 10.1186/s12889-020-10126-4.

[4] P. Kostkova, "Grand Challenges in Digital Health," *Front Public Health*, vol. 3, p. 147199, May 2015, doi: 10.3389/FPUBH.2015.00134/BIBTEX.

[5] A. Aldosery *et al.*, "MEWAR: Development of a Cross-Platform Mobile Application and Web Dashboard System for Real-Time Mosquito Surveillance in Northeast Brazil," *Front Public Health*, p. 1623, 2021.

[6] S. Lozano-Fuentes *et al.*, "Cell phone-based system (chaak) for surveillance of immatures of dengue virus mosquito vectors," *J Med Entomol*, vol. 50, no. 4, pp. 879–889, Jul. 2013, doi: 10.1603/ME13008.

[7] J. A. Uelmen *et al.*, "Global mosquito observations dashboard (GMOD): creating a user-friendly web interface fueled by citizen science to monitor invasive and vector mosquitoes," *Int J Health Geogr*, vol. 22, no. 1, pp. 1–9, Dec. 2023, doi: 10.1186/S12942-023-00350-7/FIGURES/3.

[8] "Mosquito Alert. 'Citizen science to investigate and control disease-carrying mosquitoes.'" Accessed: Feb. 19, 2024. [Online]. Available: https://www.mosquitoalert.com/en/

[9] "A Community for Naturalists · iNaturalist." Accessed: Apr. 29, 2024. [Online]. Available: https://www.inaturalist.org/

[10] L. Sousa *et al.*, "VazaDengue: An information system for preventing and combating mosquito-borne diseases with social networks," *Inf Syst*, vol. 75, pp. 26–42, Jun. 2018, doi: 10.1016/j.is.2018.02.003.

[11] B. J. Johnson, S. A. Ritchie, and D. M. Fonseca, "The State of the Art of Lethal Oviposition Trap-Based Mass Interventions for Arboviral Control," *Insects*, vol. 8, no. 1, Mar. 2017, doi: 10.3390/INSECTS8010005.

[12] A. Aldosery, D. Vasconcelos, M. Ribeiro, N. Nunes, and P. Kostkova, "Mosquito Ovitraps IoT Sensing System (MOISS): Internet of Things-based System for Continuous, Real-Time and Autonomous Environment Monitoring," *2022 IEEE 8th World Forum on Internet of Things, WF-IoT 2022*, 2022, doi: 10.1109/WF-IOT54382.2022.10152111.

[13] D. Vasconcelos, N. Nunes, M. Ribeiro, C. Prandi, and A. Rogers, "LOCOMOBIS: A low-cost acoustic-based sensing system to monitor and classify mosquitoes," in *2019 16th IEEE Annual Consumer Communications and Networking Conference, CCNC 2019*, Institute of Electrical and Electronics Engineers Inc., Feb. 2019. doi: 10.1109/CCNC.2019.8651767.

[14] C. Englbrecht, S. Gordon, C. Venturelli, A. Rose, and M. Geier, "Evaluation of BG-Sentinel Trap as a Management Tool to Reduce Aedes albopictus Nuisance in an Urban Environment in Italy," *J Am Mosq Control Assoc*, vol. 31, no. 1, pp. 16–25, Mar. 2015, doi: 10.2987/14-6444.1.

[15] E. P. Morera, I. de la Torre Díez, B. Garcia-Zapirain, M. López-Coronado, and J. Arambarri, "Security Recommendations for mHealth Apps: Elaboration of a Developer's Guide," *J Med Syst*, vol. 40, no. 6, pp. 1–13, Jun. 2016, doi: 10.1007/S10916-016-0513-6/TABLES/13.

[16] A. Rubio-Solis, T. Massoni, A. Musah, G. Birjovanu, W. P. Dos Santos, and P. Kostkova, "Zika virus: Prediction of Aedes Mosquito Larvae Occurrence in Recife (Brazil) using online extreme learning machine and neural networks," *ACM International Conference Proceeding Series*, pp. 101–110, 2019, doi: 10.1145/3357729.3357738.

[17] E. Angulo and X. Ferre, "A case study on cross-platform development frameworks for mobile applications and UX," *ACM International Conference Proceeding Series*, vol. 10-12-September-2014, Sep. 2014, doi: 10.1145/2662253.2662280.