The Earth Metabolome Treasure Quest: Uncovering Earth's Chemodiversity Through Citizen Science

1. **Summary** - *one page max*

Every living organism on Earth synthesises a vast array of chemical compounds. That's chemodiversity in a nutshell! It is the chemical tapestry woven by living organisms, from the building blocks of life to specialised molecules with unique functions. It provides valuable resources for human health, ecosystem functioning and ecological & cultural heritage. Therefore, understanding chemodiversity is crucial for appreciating biodiversity and its impact on human well-being. Despite its significance, knowledge of chemodiversity is concentrated among a select few research communities, and the general public has a limited and often distorted understanding of the topic. At the Earth Metabolome Initiative (EMI), we are building a knowledge base of chemodiversity and utilising computational methods to bridge gaps in our understanding of life sciences.

This Agora project will combine the strengths of expert researchers, skilled citizen science and communication specialists, and enthusiastic citizens to explore the depths of local chemodiversity. Our project will engage citizens with a passion for biodiversity by presenting chemodiversity exploration as a treasure quest to discover the next most important organism(s) to profile. During this project, we will facilitate citizens' direct interaction with experts, improve their knowledge and foster collaborative discovery, by involving them in research project design and implementation, thus indirectly shaping potential research questions in the field of chemodiversity.

We will utilise the established online social network of iNaturalist – known for its citizen science focus on biodiversity – and OneZoom.org tree of life explorer to create interactive web design elements. The physical spaces of botanical gardens in Neuchâtel and Fribourg will serve as interactive hubs. Commencing with Switzerland's multicultural population, roughly a quarter of whom are non-Swiss nationals, we aim to extend this project's reach internationally by building upon the collective expertise of citizen scientists.

To the best of our knowledge, this is the first citizen science project addressing the under-communicated field of chemodiversity. The novelty of this project lies in imparting data literacy in the chemodiversity space through data collection and creation process. Further, we will encourage at least a few 100 citizens to build their data stories and present/share it in desired formats. We propose to integrate citizen scientists' knowledge of location, landscape, and habitat of rare or under-documented organisms to streamline sample collection and analysis. This valuable information will be incorporated into the evolving knowledge graph of the EMI, thus providing concrete proof of how citizens can help science advance.

2. Project description - *max 40'000 characters (with spaces, tables and figures); max 10 pages excluding biblio*

2.1 Context

The metabolome, the entirety of metabolites in a biological sample, is a treasure trove. Its application lies in fields like human health, disease, food, nutrition, environmental monitoring, agriculture and biotechnology (Blanco and Blanco 2017, https://scholia.toolforge.org/topic/Q903667). The metabolome is a comprehensive representation of an organism's chemodiversity. Investigating chemodiversity is crucial for understanding the chemical foundations of biological diversity. This is a monumental task demanding a collaborative effort involving both scientific experts and the wider public. Knowledge of chemodiversity can empower the general public to appreciate the myriad forms of biodiversity and participate in its conservation. Such an educational initiative can enable the general public to understand scientific advances in the field of biodiversity and its impact on human health, thus allowing them to make informed decisions. Ultimately, chemodiversity knowledge can contribute to a more informed and engaged citizens capable of making positive impacts on the planet.

The general understanding of the life sciences starts with organisms, their size, shape, and genes. Then comes the proteins – many of which are enzymes involved in pathways required for proper functioning of organisms – and metabolites – the compounds biosynthesized by organisms. While the connections between organisms, genes, proteins have been well-documented (Manzoni C *et al*, 2018), the mechanistic understanding of metabolites and pathways in organisms have suffered neglect over the years due to various technical difficulties in metabolite detection, identification and mapping (Johnson and Gonzalez, 2018). This gap in scientific knowledge has led to the inadequate translation of awareness on this topic to the general public. Most people are still unaware of the chemodiversity surrounding them, thus oblivious to the numerous metabolites produced by organisms and their contributions to the pathways. Besides fragmented knowledge, there is little awareness about the full metabolic landscape of most organisms on Earth (Saleh *et al.* 2019, Chiara Ceci 2015) . A potential way to communicate information about organismal chemodiversity could be achieved by linking it to biodiversity.

Various mediums are used for communicating information about biodiversity, including botanical gardens. Botanical gardens provide a collection of living plants for the purposes of conservation, education and research. They also provide a medium for researchers active in specific research areas to communicate the emerging knowledge (Chen and Sun, 2018). A challenge in science communication lies in engaging people with the act of conserving the biological diversity around them (de Oliveira Caetano *et al.* 2023, Lange *et al.* 2022, Caroll *et al.* 2023, Geschke *et al.* 2023). In recent decades, citizen-science has emerged as a powerful tool to involve people with translating their knowledge into actions. Citizen-science is a collaborative approach that harnesses the power of the public to advance scientific knowledge, which is becoming a standard practice for collecting data on a broad spectrum of scientific topics (Lemmens *et al.* 2021, Tiago *et al.* 2017, Miller-Rushing *et al*. 2012) . Citizen-science projects like iNaturalist, biome (Fujiki and Tatsuno 2021), eBird (Wood *et al.* 2011), Flora-on and many others provide a medium to educate people about biodiversity, its loss and the need to conserve it. These projects also provide a platform to engage people in the act of conserving biodiversity. Few studies have also measured the impact on monitoring biodiversity by involving 'citizens' through mobile apps (Chozas *et al.* 2023, Atsumi *et al.* 2024).

It is clear that while botanical gardens and citizen-science apps in the biodiversity landscape provide a reliable and comprehensive way to educate and involve people, the same cannot be said for chemodiversity. Practically, to our knowledge there are no current science communication projects built with the aim of educating and engaging people in chemodiversity description. Our project aims to fill this gap by leveraging the data accumulated in the frame of our recently launched Earth Metabolome Initiative (https://www.earthmetabolome.org/) and by specifically utilising botanical gardens in Switzerland and the citizen-science projects of iNaturalist and OneZoom as a medium to reach the general public, educate them, encourage them to implement their knowledge and contribute to the ongoing research in chemodiversity (Figure 1).

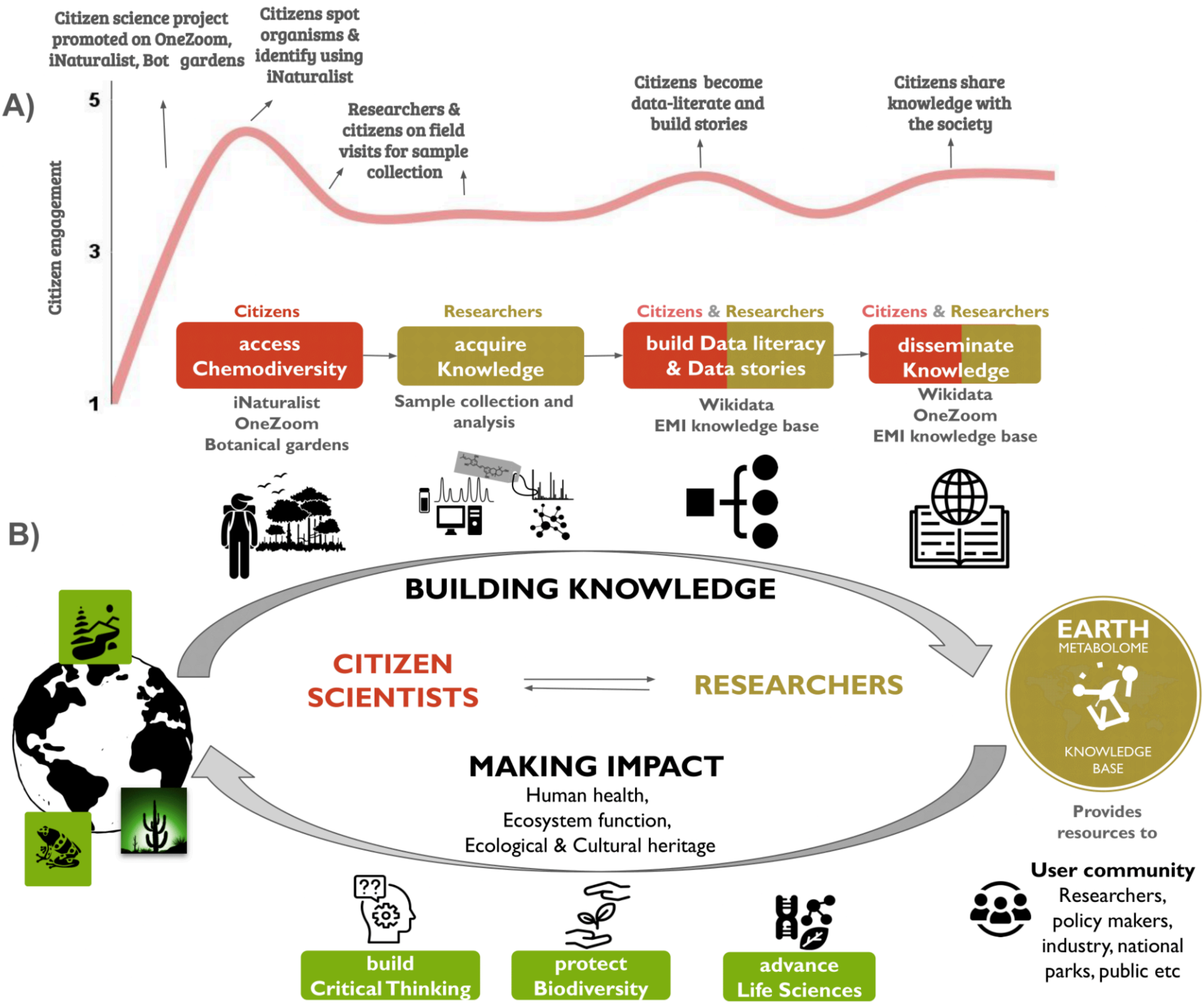

Figure-1: Project details of the Earth Metabolome Treasure Quest (A) anticipated Citizen journey and (B) broad overview of the project combining the Citizen Science Project and the Earth Metabolome Initiative

This Agora project has the following objectives:

1. To raise awareness among citizens about metabolome and global chemodiversity
2. To engage citizens in joining the Earth Metabolome Initiative by observing organisms of high interest, collecting associated data regarding their chemodiversity
3. To increase citizens' data literacy and understanding of the importance of data science for biodiversity conservation

Our potential target group will be individuals of all ages with a general interest in biodiversity, but little-to-no knowledge of chemodiversity (e.g. visitors of the botanical garden, NGOs like Pronatura, users of the iNaturalist and OneZoom).

Through this novel project, we will introduce our target group to the vital concepts of chemodiversity and 'biodiversity for health', thereby educating them that 'chemicals' are not necessarily 'synthetic'. We will thus democratise the concepts of Life's chemistry. We will combine the power of the online social network of iNaturalist, interactive web design by OneZoom.org and physical interactive space in botanical gardens of Neuchatel and Fribourg. We will create a digital and physical space for the citizens to interact directly with the researchers involved in the underlying research project on chemodiversity, use their knowledge and share their findings.

Project's relation to own current research

In 2022, E Defossez and PM Allard launched the Earth Metabolome Initiative (EMI), aiming to document metabolite accountability for all known species on planet Earth following the FAIR (Findable, Accessible, Interoperable, Reusable) guidelines (Wilkinson *et al.* 2016). In Switzerland, Defossez and Allard launched the Digital Botanical Gardens Initiative (DBGI) as a pilot project to document the chemodiversity in botanical gardens across Switzerland. DBGI and EMI are supported by Swiss Open Research Data Grants (CHORD) in Open Science I, a program coordinated by Swissuniversities and the Swiss National Science Foundation (Anticipating the Chemistry of Life - IC00I0-227830). In addition, the following green paper and peer-reviewed research by the Defossez and Allard labs as well as collaboration partner labs, strengthens the scientific ties of our proposed science communication project to our own research.

(a) Green paper - The Digital Botanical Gardens Initiative (https://www.dbgi.org/dbgi-green-paper/).
(b) Gaudry A *et al*. A Sample-Centric and Knowledge-Driven Computational Framework for Natural Products Drug Discovery. ACS Cent Sci. 2024
(c) Rutz A *et al.* The LOTUS initiative for open knowledge management in natural products research. Elife. 2022
(d) Wolfender JL *et al*. Metabolomics in Ecology and Bioactive Natural Products Discovery: Challenges and Prospects for a Comprehensive Study of the Specialised Metabolome. Chimia (Aarau). 2022
(e) Defossez E *et al*. Spatial and evolutionary predictability of phytochemical diversity. PNAS 2021

The scientific findings of E Defossez on plant metabolome diversity and PM Allard's computational metabolomics research within the framework of DBGI and EMI will enrich our citizen science project. We will engage citizens in exploring chemodiversity under varying environmental conditions (E Defossez). This will be done using tours across interactive tree of life by OneZoom.org (J Rosindell and Y Wong), followed by encouraging citizens to contribute to filling the gap in the chemodiversity data by recording and reporting their findings through iNaturalist platform. This will be followed by researchers from both Defossez and Allard labs reviewing the citizen's findings, collecting samples and performing metabolomics analysis while accompanying the citizens to the physical spot of their finds. Following the scientific analysis, the knowledge generated thereof will be integrated in the knowledge graph of EMI (PM Allard), the results will be discussed with and presented to the contributing citizens and the global citizen-base created during the science communication project.

2.2 Methods

Target audience and the chose means of communication

Biodiversity - a premise for chemodiversity - is a popular topic amongst people of various ages, genders, profession, places irrespective of their educational backgrounds (de Oliveira Caetano *et al.* 2023). Moreover, general advances in technology like access to mobile apps and websites have reached most individuals from all walks of life and are no longer limited to the privileged few. For instance, the informal conversations on the iNaturalist forums indicate that the users of the app could be as young as 13 years and as old as 75 years. To launch this project, we will target individuals and groups with a general interest in biodiversity and human health. This target public provides a strong foundation for sharing knowledge about chemodiversity, as their existing interest in biodiversity can be leveraged to increase engagement.

Our project will use the visitor base of the iNaturalist mobile app (~7 million registered users worldwide), OneZoom (~28,000 users per month) and botanical gardens of Switzerland, mainly Fribourg and Neuchatel (~200,000 visitors every year). Therefore, the potential target public will be individuals with a general interest in biodiversity as well as biodiversity conscious families with kids visiting the botanical gardens.

Project design and elements

The project is divided into 5 work-packages (WP)

In **WP1-Technological Development**, chemodiversity-specific interactive elements will be added to the OneZoom.org tree of life. OneZoom.org is a platform to interactively view the tree of life based on the open tree of life's taxonomy (Rees J *et al* 2017, ott3.7). An improved version of the tree will be created by OneZoom team (J Rosindell, Y Wong) to incorporate the visualisation by availability of chemodiversity in EMI knowledge base (Rutz A *et al* 2022, Gaudry A *et al* 2024). This will involve implementing new methods enabling OneZoom to handle colour and style data across over two million leaves of the tree (representing nearly all described species) whilst remaining performant for end users. Three guided virtual tours around the tree will be created to provide conceptual and factual information about chemodiversity - one each for plants and arthropods, and a third one for general facts about the gaps in chemodiversity. A user-experience journey will be developed on the EMI website (https://www.earthmetabolome.org/), which we will directly integrate with the OneZoom's tree of life explorer to show clearly the complex interactions between evolutionary trees and chemodiversity information.

In **WP2-Citizen Scientist Recruitment and Training,** we will employ different promotional measures (Table-1) to reach the target public and encourage them to contribute to the EMI. We will engage, train and retain the citizens through following four approaches :

a) We will use the **OneZoom** tree of life overlay from WP1 to emphasise the next most important taxonomic branch for gathering chemodiversity information. This will be embedded on the EMI web-page (PM Allard and E Defossez's team). The page will be equipped with the information on glaring gaps in chemodiversity information for all organisms linking to the embedded tree and draw attention of the target public through compelling visuals.

b) We will announce the science communication project at the EMI **iNaturalist** account. We will use this to communicate the exact requirements for observations to qualify for the EMI account (PM Allard and E Defossez's team). It will have information for the OneZoom tree of life describing the missing link in the chemodiversity and encouraging participants to report their observations and the exact sites. iNaturalist uses computer vision models to identify observations based on prior identifications provided by its users. Citizens will upload relevant observations to the EMI account, identify it as one of the organisms from iNaturalist's taxon list or undocumented organism, whichever applicable. Finally, this account will have a blog section, where citizens can write their data stories (see point (d) below) and share with the wider community.

c) We will organise informational events in **botanical gardens** to communicate the citizen science project to the public. The public will have a one-to-one interaction with the researchers (E Defossez, PM Allard). The team will provide an overview of the OneZoom tree and the glaring gaps in chemodiversity research. The target public will be educated about the importance of iNaturalist, creating accounts on iNaturalist, identify their spotted observations using iNaturalist app and add corresponding metadata. The participants will be given opportunities to ask questions about the project, and how their contribution could benefit chemodiversity research. A strong emphasis will be placed on responsible citizen science practices (details in risk management).

During these events, the participants (whose observations were selected by EMI) will be invited to share their experiences amongst themselves and with the researchers, particularly their experience with spotting the rare organisms (degree of difficulty), reporting their observations on iNaturalist, general experience with providing site information to the researchers and subsequent on-site visits. The participants will be provided feedback on their contribution and those who were engaged the most (assessed by quizzes and intensity of participation) will be awarded gifts as incentives.

d) The participants will be invited to contribute to the **Wikidata** knowledge base by creating and curating structured entries of rare or undocumented organisms and/or their chemodiversity. Wikidata serves as the central repository for information used by platforms like Wikipedia in the Wikimedia movement. It will help promote **data literacy** as we encourage citizens to use Wikidata as a basis for creating and sharing their own data stories over platforms like iNaturalist blogs, social media or through meetups in botanical gardens. Experienced researchers in chemodiversity knowledge management (E Defossez's team) and Wikidata (Daniel Mietchen) will provide training and support to the participants. Participants can choose to focus solely on knowledge creation or combine their contributions with observations, as described in WP-3, giving them the flexibility to engage at their pace.

In **WP3-Onsite Visits and Data Collection**, the participants will be invited to contribute their observations digitally through Earth Metabolome Initiative iNaturalist project.The iNaturalist's computer vision models will aid in assigning identifications to the citizen's observations and if no identification is available with even reasonably good quality images, the observation will be counted as undocumented. Following this, project leaders and researchers will verify the authenticity and suitability of the observations and follow-up with the selected contributors, in case the observation is a rare or undocumented plant or arthropod, not listed in EMI knowledge base. In such cases, the researchers (Teams of E Defossez and PM Allard) will accompany the contributor to the site where the observation was made and collect the samples from the organism of interest. This will allow a direct interaction of the researchers and the non-specialized participants. Following the collection, the samples will be brought to the lab and processed for profiling metabolomics data and updated in EMI knowledge base. To minimise risks associated with sample collection, we will not consider sampling from vertebrates at this stage of the project.

In **WP4-Promotion and Communication**, we will implement use a diverse range of channels to reach individuals across various demographics and interests (age, interest, social media activity, etc; Table-1).

Table 1: Marketing and advertising

Format	Target group(s)	Indicators
Websites	Visitor base of OneZoom and iNaturalist, botanical gardens	EMI, OneZoom (~28,000 visitors per month, ~1500 per day), iNaturalist-EMI (~18,000 visitors from Switzerland, ~7 million registered users worldwide)
Public events and flyers	People visiting botanical gardens	Presentation of projects in botanical gardens of Fribourg, Neuchatel (WP-3); Flyers in all botanical gardens of Switzerland listed in Hortus Botanicus Helveticus.
Social Media	People active on social media	LinkedIn, Instagram (TBD), iNaturalist, you-tube. Use of existing visitor base of social media accounts active in biodiversity (e.g: @MassSpecEverything)
Radio, Podcasts	People listening to audio	Leverage past EMI podcast episodes like CQFD and occasional OneZoom

	shows	podcasts
Promotional videos	People actively watching you-tube channels.	Video explaining the concept behind EMI.

In **WP5-Impact Assessment and Documentation,** the citizen science project will undergo a comprehensive evaluation to assess its scientific outcomes, data quality, participant satisfaction, and broader societal impact (Manuela Dahinden; see 2.4 - Expected impact). We will employ a mixed-methods approach, incorporating quantitative and qualitative techniques. This includes surveys and structured interviews to understand participant motivations, attitudes towards science, and knowledge gains. Guiding research questions based on science communication include- R1: What raises interest in participating in the citizen science project (on chemodiversity)? R2: What type of audience would participate? R3: What kind of changes (cognitive, emotional, attitudinal, behavioural) can be realistically achieved? The results will be published in a peer-reviewed journal.

Position of the project in relation to the best practices in public science communication

Science communication is shifting from a passive model, emphasizing limited audience research, to an active model of public participation (Deng 2024). In recent years, citizen science has gained greater attention as a way of tackling research questions that otherwise could not be addressed without the involvement of large numbers of data collectors, and also as a method of engaging the public in the scientific process with the goal of improving scientific literacy (Bonney et al. 2009). Our project goes a step further by providing participants a chance to accompany researchers during sample collection, allowing them to learn about sample collection, rather than directly sending samples off to a lab. We will also provide the citizens an opportunity to create knowledge through wikidata and build their data stories. The European Citizen Science Association, ECSA, has established key principles that underlie good practices in Citizen Science (ECSA, 2015). Our project fulfils several of these principles.

a) We will provide citizens with the basic tenets of chemodiversity concepts and involve them in generating new knowledge (WP2). Thus, we will facilitate a knowledge exchange bridge benefitting both professional scientists and citizen scientists.
b) We will treat this project both as a science communication project, and a research approach, thus controlling for bias, limitations, data quality and risks (summarized in WP3).
c) We will provide feedback to citizens on their efforts, data quality and participant experience, encouraging them to get involved in wider societal discussions and policy-making.
d) We will help citizens realize the relevance of chemodiversity data by providing them a contextual understanding of the relationship between biodiversity, human health and chemodiversity (Figure-1), thus making it easier to grasp complex concepts and implications of their efforts.
e) From the research perspective, we will build a comprehensive database of organisms and their metabolomes using the data generated from this citizen science project.

A key responsibility of any citizen science project is to evaluate its environmental impact. Nature tourism and photography can have negative effects on the environment (Davis *et al* 2024), and while our project is not directly focussed on these activities, they could be incidental outcomes. We will provide citizens with guidelines for ethical behaviour to mitigate these risks (for instance, the seven principles of leave-no-trace).

The innovative element of this project is integration of data literacy training into a citizen science project. **Data literacy** involves both the technical skills to collect and analyze data, and critical thinking needed to interpret and apply data in various contexts (Gibson and Mourad, 2018). Citizen science projects can serve as powerful catalysts for developing data literacy (Kjelvik and Schultheiss, 2019) and co-design of environmental monitoring innovations

(Happonen et al 2022). As explained in WP2, we will provide training to citizens in sample collection and Wikidata entry creation. This direct involvement will foster an understanding of how data is generated and the importance of accuracy and consistency. This way, we will enable citizens to reflect on what they have learnt in their training and build knowledge for the society. We believe that data-literate communities are better equipped to advocate for conservation efforts and hold decision-makers accountable. In essence, this citizen science project will offer an accessible, practical entry point for individuals to build data literacy. Through continued engagement and education, participants can evolve from data collectors to informed data users and advocates for data-driven decision-making in their communities.

Integration into existing initiatives and beyond

The knowledge generated in this project will undergo quality control and once passed will be a direct addition to the ongoing metabolome profiling efforts of DBGI and EMI. The knowledge generated by the citizens will be integrated in the current knowledge base of EMI and provided as an open-access resource.

The long-term goal of this citizen science project is to collect and disseminate chemodiversity knowledge worldwide. The overall idea is to inculcate critical thinking amongst the public, enabling them to advocate for sustainable evidence-based solutions and engage in public discussions on science and policy measures related to global chemodiversity. E Defossez and PM Allard are continuously expanding the DBGI and EMI initiatives by securing third-party funding. Within the respective funding limitations, a citizen science component will be included wherever possible, thereby continuing the original Agora project and raising awareness about chemodiversity amongst the non-specialized world citizens.

Contribution to diversity awareness

One of the long-term goals of this project is to reach people from all strata of the society, irrespective of their knowledge in bio/chemo-diversity. For this purpose, we will incorporate several measures to make our project accessible to all.

a) Usability and accessibility are key in designing digital platforms for individuals with visual impairments. Therefore, we will incorporate audio transcripts where possible like panels in botanical gardens or provide information on using screen reader plugins with different browsers for navigating the OneZoom, EMI and iNaturalist websites - JAWS with Chrome, NVDA with Firefox, VoiceOver with Safari, Narrator with Edge.
b) We will use gender friendly language in all informational events as well as one-to-one direct conversations to ensure gender diversity and inclusion.
c) Our means of communication through websites like OneZoom.org and iNaturalist, are accessible to people from all strata of society irrespective of their gender, age, and social status.
d) In Switzerland, 27% of the population are foreign nationals (Stats from BFS). We will increase awareness amongst them to explore the surroundings in their home countries by providing location based information on organisms through OneZoom (location tab from the Global Biodiversity Information Facility) and iNaturalist.

Promotion and development of dialogue between scientists and society

This project not only aids in encouraging public dialogue with scientists (Table-1), but also benefits from the public knowledge. Three areas where we are directly creating such dialogues are

a) In-person interaction and collaboration between researchers and citizen scientists for collecting plant samples from identified locations during onsite training and visits (WP3). We expect 10-50 site visits during the duration of the project.
b) Under the guidance of experts, encouraging citizen scientists to create and disseminate knowledge through Wikidata (WP2). Online platforms like Zoom, Big Blue Button and others will be used for such training (~200) including general informational events (~2-4).

c) Informational events in botanical gardens (WP2). We plan to organize at least 4 such events, including party-like events for citizens to share their experience.

Allowing them to look for samples at their convenience, this project benefits from the design of mini-projects by the citizen scientists. During sample collection the citizens will provide their regional and traditional knowledge to the researchers. In turn, researchers will provide information on what part of the sample to collect and how. This creates a two-way bridge of knowledge dissemination and joint development of the research methodology, thus enhancing dialogue between scientists and society.

_2.3. Implementation

Schedule for the project, including different milestones and interim objectives

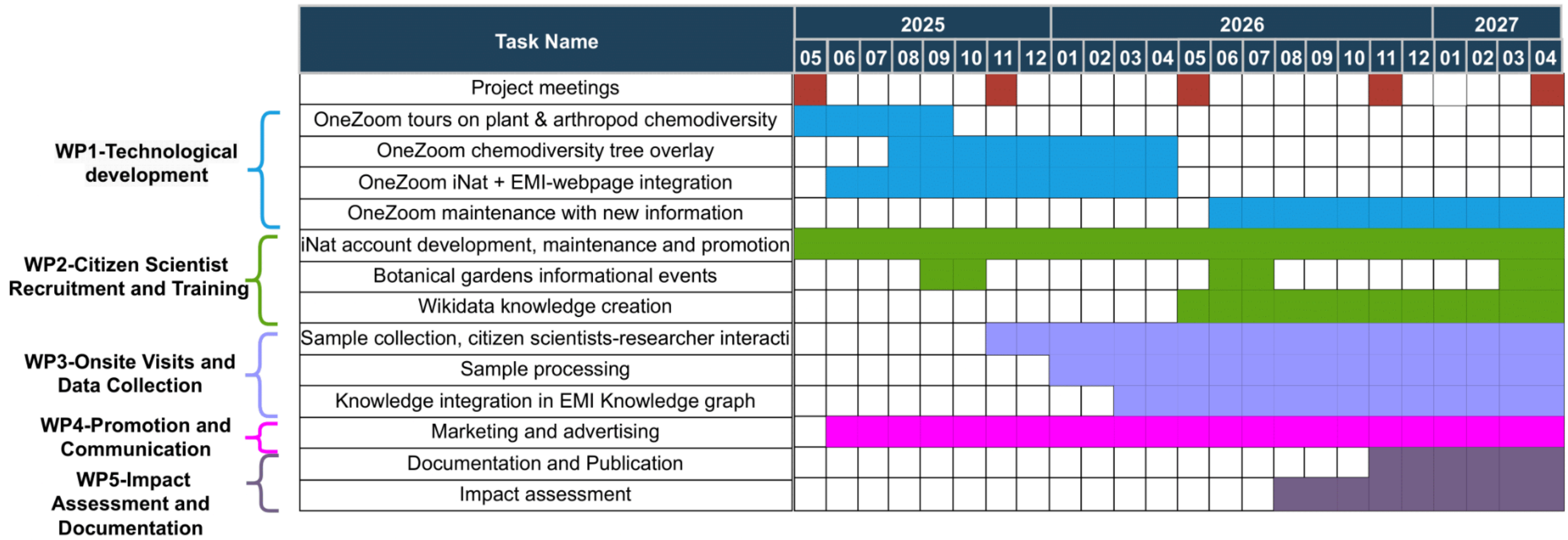

Figure-2: Gantt chart with timeline, milestones and objectives. Colors are specific to work-package or activities

Roles and responsibilities of the project team

Table 2: Project team

Name and affiliation	**Roles and responsibilities**	**Expertises**
Applicants		
Pierre-Marie Allard (University of Fribourg)	WP-1,2,3,4, Informational events and interaction with participants	Computational solutions for natural products research
Emmanuel Defossez (University of Neuchatel)	WP-2,3,4, Informational events and interaction with participants	Plant chemical ecology and biostatistics
Project partners		
Yan Wong (OneZoom)	WP-1, OneZoom tours and tree overlay	OneZoom initiator, Evolutionary genetics, Collaborated with Richard Dawkins on the book 'The Ancestor's Tale'.
James Rosindell (OneZoom)	WP-1, OneZoom tours and tree overlay	OneZoom initiator, Biodiversity theory
Daniel Mietchen (FIZ Karlsruhe)	WP-2, Trainings for Wikidata entry creation	Open research data, biodiversity, citizen science, Wikimedia, knowledge graphs
Collaborators		
iNaturalist team	WP-2, iNaturalist engagement	Citizen science, biodiversity
Communication expert		
Manuela Dahinden	WP-5, Promotional measures, design	Science communication and education, Coordination of 5

(INTERES GmbH)	of evaluation methods for impact assessment	Agora projects and one citizen science project.

Risk management plan

Table 3: List of potential challenges and ways to overcome them. Adapted from the recommendations of the BiodivERsA Citizen Science workshop and additional literature (Geoghegan et al 2016; UKEOF 2017, Pocock et al 2018b).

Potential challenges	**Ways to overcome them**
Low-level risks	
Poor data quality Scientific bias and sampling issues Challenges using tools or platforms by citizens	Ensure protocols and technical tools are well-defined and suitable to use for the target public. Quality control by expert researchers, provide support and training to citizens.
Difficulty attracting and retaining participants Low engagement in events or platforms.	Use appropriate communication channels (OneZoom, iNaturalist, Wikidata, social media), Organize events in local languages.
Project management Lack of time investment by researchers, Lack of money	Ensure proper training and mobilization of scientists and student volunteers. Find additional funding.
Data management Issues linked with participant data privacy and safety.	Ensure adoption of legal frameworks (e.g. GDPR regulation) ,clear privacy policies, transparent data use and data ownership (Resnik, 2019).
Scientific impact - Lack of meaningful outcomes.	Align activities with scientific goals and provide feedback to participants.
High-level risks	
Technical barriers Language and technical barriers (access to technology, scientific terminology, lack of user-friendly platforms)	Organise meetings and Q/A sessions between scientists and citizens, Offer multi-language support, Flexibility with technical aspects (e.g. accept contributions by email)
Environmental impact Impacts on biodiversity (Davis *et al* 2024)	Establish codes of ethics and practices for responsible conduct during citizen science activities (e.g.: leave not trace) with least damage to biodiversity.

2.4. Expected Impact

The ultimate goal of DBGI and EMI is to use all the gathered metabolic information to support, and implement conservation efforts worldwide. We believe that by providing chemical maps of the landscape it will be possible to contribute to the prioritisation of conservation and restoration targets. For example, by identifying places that are poor in species diversity but rich in a rare chemodiversity. By engaging citizens in the collection, analysis and dissemination of data, we expect a valuable increase in data with benefits both for science (e.g. more impactful publications, global coverage, awards, follow-up grant) and society (e.g. efficient environmental policies, uptake into education, increase in global conservation efforts). The outcomes of this project go beyond production of data/information. More people will understand the relevance of chemodiversity for the environment, food and medicine, health and well-being and the need for its conservation. Citizens will gain data literacy - a foundational skill that supports their decision-making and trust in science.

Expected quantitative and qualitative impact

Outputs: Primary outputs include different outreach activities created to inform, educate, or engage audiences (e.g., 4 community events in the botanical gardens, 2-4 training events, 3 newly implemented guided virtual tours at OneZoom with ~28,000 visitors/month, one user-experience journey on the EMI website, few hundred created and curated structured Wikidata entries), as well as the type and number of online communication (e.g., 2 podcasts, 2 video tutorials, 5 shared data stories in social media and iNaturalist blogs) and marketing channels (e.g., media relations or advertisements) used to promote these activities. Secondary outputs include the 1 expected media coverage and 1000 new followers, 1000 visitors at the EMI website, 50 new accounts at iNaturalist.

Outcomes: Direct outcomes include at least 50 people participating in the citizen science project and their immediate feedback or response. Meaningful indicators will be whether participants have developed a greater interest in or enjoyed being exposed to an activity. Indirect outcomes (medium-term effects) include increase in people's cognitions (e.g., data literacy and environmental knowledge), emotions (e.g., enthusiasm and fascination) and pro-environmental behaviour (e.g. advocacy).

Methods and criteria that will allow assessing the success of the project

The Citizen science project will be evaluated for its scientific output, data quality, participant experience and learning outcomes and wider societal or policy impact (Kieslinger et al. 2017, Jordan et al. 2012). We will implement an empirical evaluation process that makes use of quantitative and qualitative research methods, including surveys and structured interviews that explore citizens' motivations to participate in the projects activities, knowledge gains, or behavioural intentions. Iterative rounds of feedback and success measurement will improve usability and accessibility of softwares.

We will employ multiple techniques to evaluate science communication projects at various stages (Table 4). While process-level evaluation identifies the activities' or programs' operational strengths and weaknesses, impact-level evaluation is concerned with assessing the overall goals of the activities or programs and the benefits to the participants and recipients of results. In this way, the evaluation will serve learning and continuous improvement of the project. An evaluation of individual learning outcomes (cognitive, affective, behavioural) aims to help project managers to improve overall project outcomes, reach new audiences, promote learning opportunities, and increase project longevity and impact.

Table 4: Evaluation methods

Activities	**Quantitative indicators**	**Qualitative indicators**	**Evaluation methods**
Process-level			
Participation in the citizen science project	Number of people participating (age, gender, demographic background) Type of participation (sampling, experimenting, dissemination) Satisfaction, motivation and inquiry skills	Level of motivation and interest in the topic Giving (positive, mixed, negative) feedback to technical difficulties or asking questions about the scientific process and methods Learning outcomes e.g. environmental knowledge or data literacy	Q/A Pre- and post-knowledge tests with participants (adapted to Gibson and Mourad 2018; Kjelvik and Schultheis 2019)
Online platforms	Number of people	Quality of data stories	Quality assessment as per guidelines

(OneZoom, Wikidata)	participating (demographic background)		of WikiProject Data Quality
Marketing and advertising	Number of reports in TV, radio, print and online Number of social media posts by participants and number of followers, likes of posts by the project team		Content analyses of media resonance, website or social media analyses
Events in botanical gardens	Number of people participating (age, gender, demographic background)	Level of engagement with scientists Type of (research and technical) questions inquired by participants	Autonomous and informal feedback (snapshot interviews, before and after drawing, guestbooks, feedback cards)
Impact-level			
Contribution to science	Number of publications Number of contributions to iNaturalist-EMI account	New or refined research questions based on the participants input	
Follow-up activities	Number of people participating in conservation efforts, public discussions and policy-making	Changes in people's cognitions (e.g., knowledge and understanding), emotions (e.g., enthusiasm and fascination), attitudes (e.g., opinion change), or pro-environment behavior.	Standardized surveys, semi-structured interviews or focus groups, participant observations, scenario-based assessments, knowledge tests (adapted from Somerwill and Wehn, 2022).

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