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RESEARCH

Exploratory conversations with biodiversity-oriented civil society groups on the potential applications of gene drive-modified mosquitoes for malaria control in Tanzania

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Abstract Gene drive-modified mosquitoes (GDMMs) are gaining attention as sustainable tools to complement existing malaria control strategies. Their ability to self-propagate and spread through wild mosquito populations offers the promise of low-cost, long-lasting impact, but also raises ecological, ethical, and governance concerns. In this evolving debate, civil society organizations (CSOs) are pivotal actors in shaping dialogue, representing community concerns, and influencing policy decisions. This study examined the perspectives and recommendations of biodiversity-oriented CSOs on the governance, testing, and potential application of GDMMs for malaria control in Tanzania. An exploratory qualitative design was employed, involving eight in-depth interviews, one focus group discussion, and three large group discussions with representatives from ten biodiversity-focused CSOs in Tanzania. Participants were selected purposively based on prior involvement in national or regional dialogues related to biotechnology; and the discussions focused on concerns, uncertainties and needs associated with testing and potential use of GDMMs for malaria control, as well as the balance of prospective benefits against long-term environmental risks. Transcripts were analyzed thematically using NVivo 12 Plus. Participants expressed cautious support for research on GDMMs for malaria control but raised concerns about scientific uncertainty, limited local expertise, inadequate transparency, potential transboundary effects and technological dependency. They emphasized the importance of generating robust, context-specific evidence before considering any environmental releases of gene drives; and highlighted concerns over inadequate accountability, particularly the lack of clarity on who would assume responsibility if adverse outcomes arise. They also advocated for early, inclusive, transparent, and continuous engagement with both target communities and the broader public. Lastly, to ensure objective and impartial oversight, they recommended development of local expertise that is independent of technology developers and sponsors. The CSOs' perspectives were diverse but broadly aligned with the precautionary principle, calling for preventive action amid uncertainty, clear accountability, and the pursuit of safer alternatives. Although many expressed serious

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reservations about gene drive mosquitoes, there was a shared recognition that research on the technology is necessary, provided it is conducted under controlled, transparent, and auditable conditions. Overall, these exploratory discussions underscored the need for: (i) balanced dialogue between advocates and skeptics, (ii) robust ethical and regulatory frameworks covering the full life cycle of the technology, (iii) sustained community and stakeholder engagement from the early stages of research and development, (iv) enhancements of in-country capacity, and (v) national sovereignty in decision-making regarding GDMMs. Demonstrating and effectively communicating these elements will be as critical as ensuring their existence.

Keywords Civil society organizations · Biodiversity · Gene drive modified mosquitoes · Malaria

Background

The development of gene drives technologies has opened new possibilities for the control of malaria, a disease that affects ~ 250 million people and claims ~ 600,000 lives annually, mostly in sub-Saharan Africa (Naidoo and Oliver 2024; Abraham et al. 2025; AUDA-NEPAD. 2025). Gene drives are engineered genetic systems designed to bias inheritance, enabling modified traits to spread rapidly through interbreeding wild populations (AUDA-NEPAD. 2025). Gene drive-modified mosquitoes (GDMMs) are currently being investigated as a potential complementary tool to accelerate malaria elimination prospects, by either reducing populations of malaria vectors or modifying them to prevent malaria transmission (Simoni et al. 2020; Marshall and Akbari 2016; Carballar-Lejarazú et al. 2020). While this technology has gained growing international attention for its potential, its eventual success will require thoughtful considerations of ethical, ecological, and governance aspects, to ensure that it is implemented responsibly, especially in regions where it may be introduced (Hammond and Galizi 2017; Resnik 2015).

Tanzania is one of the countries significantly contributing to malaria cases worldwide, with nearly nine million cases and more than 25,000 deaths recorded in 2022 alone (WHO 2024). The disease is transmitted primarily by three mosquito species; *Anopheles arabiensis, Anopheles gambiae* s.s., and *Anopheles funestus*, each exhibiting varying levels of dominance and distribution across different ecological settings within the country (Mwalimu et al. 2024). This complex vector landscape, combined with the high malaria burden, positions Tanzania as a potentially suitable setting for testing and future deployment of GDMMs (2024). However, this potential also requires robust regulatory systems, ethical oversight mechanisms, and informed stakeholder participation (Lavery et al. 2008).

African Conversations is an African-led initiative that brings together diverse African stakeholders to reflect on emerging health issues and technologies, identify local needs, and ensure that innovations serve African populations effectively and ethically, to ensure inclusive and informed dialogue that elevates African voices, builds understanding of new technologies, and inspires collective action toward better health outcomes. In recent years, African Conversations initiative has sought to bridge the gaps in stakeholder participation by facilitating in-depth dialogues with a broad range of stakeholders, to ensure that African perspectives are meaningfully integrated into ongoing research and development of emerging technologies like GDMMs (Finda et al. 2023). So far, the initiative has documented key insights, concerns, and recommendations from stakeholders in over 25 African countries on the ethical and responsible introduction of GDMMs in specific African contexts (Finda et al. 2023). These have included policymakers, regulatory authorities, researchers, academics, and community-based representatives such as faith-based institutions, traditional and political leaders, and civil society organizations (CSOs) (Finda et al. 2023). While GDMMs were generally met with optimism by a majority of the stakeholders (Finda et al. 2020, 2021, 2023), one group, the CSOs, consistently expressed higher levels of skepticism and concerns regarding the development and potential use of these technologies in Africa.

Civil society organizations are non-profit entities that operate independently of government and represent the interests, values, and voices of different segments of society (Salamon and Anheier 1997; Scholte et al. 2003). They include a wide range of groups such as community-based organizations, advocacy

networks, non-governmental organizations, faith-based groups, and professional associations (Salamon and Anheier 1997; Scholte et al. 2003). CSOs often play a critical role in promoting transparency, accountability, and public participation in policy and decision-making processes. In the context of science and technology governance, CSOs serve as important intermediaries between communities, policymakers, and researchers, advocating for ethical standards, safeguarding community rights, and ensuring that innovation is aligned with social, cultural, and environmental priorities (Mali 2009). In this case, their involvement is especially important in shaping the governance of emerging technologies such as GDMMs, which have potential transboundary implications and irreversible environmental effects (Mali 2009; Matsuda et al. 2020). In such contexts of scientific uncertainty and potential ecological risk, frameworks like the precautionary principle become particularly relevant. This principle calls for preventive action in the face of uncertainty, a shift in the burden of proof to technology proponents, consideration of safer alternatives, and inclusive public engagement in decision-making (Mali 2009; Matsuda et al. 2020; Hartley et al. 2022; Kriebel et al. 2001). These elements align closely with the values CSOs often champion in their oversight and advocacy roles (Salamon and Anheier 1997; Scholte et al. 2003).

In Tanzania, many CSOs concerned with environmental protection and biodiversity conservation are organized under the Tanzania Alliance for Biodiversity (TABIO), which is dedicated to conserving agricultural biodiversity, and promoting environmentally friendly and sustainable farming systems in Tanzania (TABIO 2025). TABIO was formed in 2011 to advocate for farmers' self-determination, food sovereignty, and agroecology, while raising public awareness on issues related to agriculture, the environment, and emerging technologies (TABIO 2025). Although originally focused on agriculture, TABIO has since expanded its scope to include areas such as biocontrol technologies in health and conservation, recognizing the interconnectedness of biodiversity with other sectors (TABIO 2025). The alliance works through a structured governance system and engages a wide range of stakeholders, including smallholder farmers, pastoralists, women, youth, and indigenous communities, to influence policy and champion biodiversity-based solutions (TABIO 2025).

Despite their important role in public interest advocacy, the perspectives of CSOs on biocontrol technologies remain largely underexplored in both research and policy discourse. This gap may stem in part from the widespread perception that CSOs are inherently opposed to certain biotechnologies, largely because of their critical stance on genetically modified organisms in agriculture (African Centre for Biodiversity 2025; Scoones 2009; Sarma and Pais 2008; Pan African Visions 2025). However, it is critical to engage with voices that may be skeptical or critical, to ensure transparency, accountability, and robust public oversight (Mali 2009). For gene drives in malaria control, engaging critical CSOs early can strengthen transparency, accountability, and public oversight, while illuminating cross-cutting issues of public trust, ethical governance, community engagement, and national sovereignty that sit at the heart of responsible GDMM development (Mali 2009). Moreover, applying a precautionary lens means embracing iterative testing, independent risk assessment, and robust monitoring frameworks before field deployment, rather than after potential harms have emerged (Mali 2009; Matsuda et al. 2020; Hartley et al. 2022; Kriebel et al. 2001). It also prioritizes open, participatory dialogue that includes proponents and critics alike, reduces technological dependence through diversified malaria-control portfolios, and supports co-development of regulatory and ethical standards that reflect local values and priorities (Mali 2009; Matsuda et al. 2020; Hartley et al. 2022; Kriebel et al. 2001).

The aim of this study was therefore to capture the perspectives, concerns and recommendations of the biodiversity-focused civil society groups in Tanzania on the governance, testing and potential use of gene drives for malaria control in Tanzania. Rather than excluding opposing views, this study recognizes the value of engaging with CSOs precisely because of their watchdog role, helping to ensure that the final product is ethically sound, socially responsive, and meaningfully scrutinized.

Methods

Study participants

Study participants were drawn from ten (10) of the 55 civil societies who are members of the Tanzania Alliance for Biodiversity, and included organizations

primarily focused on biodiversity protection goals related to environment, health and agriculture. Participants were selected using a purposive sampling approach, based on their previous active involvement in national and regional dialogues on biotechnology, biosafety, and genetically modified organisms. In total, fifteen organizations were contacted, and ten agreed to take part in the study, each represented by their respective spokesperson. This final group of participants reflected a broad perspectives and geographic representation across Tanzania. In keeping with the ethical standards of the study, and in response to participants' requests, no identifying personal information such as age or sex has been disclosed.

Study procedure

This study used an exploratory qualitative design, beginning with one focus group discussion (FGD) and followed by eight in-depth interviews (IDIs) and three large group discussions to capture detailed insights from CSO representatives. The FGD brought together ten CSO representatives from various regions of Tanzania, all affiliated with TABIO. This initial session provided a platform for exploring general perceptions of gene drive technologies for malaria control and identifying key themes to guide further inquiry into CSO engagement with emerging biotechnologies. Given the broad diversity of perspectives within civil society organizations, as observed in the initial discussions, and the desire by some individual participants to speak privately, a follow-up series of individual interviews was conducted to explore more in-depth insights, concerns and recommendations of the CSOs regarding GDMMs. These interviews provided a more private and flexible setting in which participants could express their views openly, particularly those that might not surface in a group environment due to social dynamics, institutional affiliations, or the sensitive nature of certain concerns. The one-on-one format also enabled participants to reflect more deeply on the implications of GDMMs, articulate specific reservations or hopes, and elaborate on their organization's stance and priorities. Depending on the participants' availability and geographic location, IDIs were conducted either in person or virtually via Zoom.

Lastly, three plenary sessions were held within a national stakeholder workshop in Tanzania, bringing together scientists, academics, regulators, policymakers, communities, political and faith leaders, and biodiversity-focused CSOs. Building on prior group-specific consultations, these sessions sought consensus on key issues that had been previously discussed, and brainstormed country-level priorities. Each of the three sessions included at least two actively participating CSO representatives. For the purposes of this analysis, the meeting transcripts were examined in detail, and specific comments from CSO participants were extracted, anonymised and thematically analysed. In total, twelve discussion sessions were held, reflecting insights from ten distinct CSO representatives.

Data processing and analysis

The IDI and FGD recordings were transcribed, and for sessions conducted in Swahili, transcripts were translated into English to allow for consistent analysis. Transcription and translation were carried out by MF, SM, and GM. Verbatim transcripts from all sessions were then imported into NVivo 12 Plus software to facilitate systematic coding and thematic analysis (NVIVO 2018). A combination of deductive and inductive coding approaches was applied as follows: for the FGD data, inductive coding was primarily used, given the exploratory nature of the discussions. However, the FGD guide also informed the creation of supplementary deductive codes based on predefined topics of interest. As for the IDI transcripts, however, deductive codes were developed from the study objectives and interview guide, while supplementary inductive codes were added through careful reading and interpretation of participant responses. Recurrent themes were identified, and illustrative direct quotations were selected to support and reflect the participants' views. Key themes that emerged from the analysis included: (i) general perspectives on GDMMs, (ii) support for continued research on GDMMs, (iii) concerns over uncertainty surrounding GDMMs, and (iv) calls for ethical community and public engagement in all stages of research and decision-making.

Results

Diverse views among CSOs

At the outset of the initial FGD session, CSO representatives were keen to emphasize the diversity of perspectives from individuals within their community. They requested that this be acknowledged before delving into further discussions, stressing that their views should not be assumed to reflect a single, unified position. Participants explained that while some CSOs are generally more conservative, others are more open and flexible, particularly when it comes to research and technology development that is not directly linked to the agricultural sector, where opposition to biotechnology has historically been more pronounced. Despite these differences, participants stressed that there was common ground in their collective commitment to ensuring genuine dialogue, mutual respect, and a balanced evaluation of risks and benefits in any conversation involving emerging technologies. One participant noted:

> *"We in the CSOs hold a variety of positions and perspectives. While we are all united in advocating for the safety of our people and the protection of the ecosystem, our approaches may differ. Some organizations tend to be more conservative and cautious, while others are more open and flexible. It really depends on the issue at hand."*

The participants further noted that the diversity of opinions within the CSO community should be seen as a strength rather than a limitation. They argued that this diversity reflected the range of constituencies they represent, from grassroots movements to more policy-focused NGOs. While their strategies and perspectives may differ, they all shared a commitment to protecting the health, environment, and rights of their communities.

General perspectives on gene drive-modified mosquitoes

With regard to gene drive mosquitoes, the CSO representatives expressed deep concerns about the risks and unknowns associated with the technology but also offered recommendations on how the technology could be approached and researched more responsibly. All participants voiced a degree of reservations about gene drive mosquitoes but there was unanimous support for continued research aimed at generating local evidence, and the pursuit of context-specific evidence to inform future decision-making. However, participants were also clear and consistent in their position that field releases should not proceed in the near future, emphasizing their concern that current knowledge and regulatory preparedness were insufficient to justify such a step, especially in Tanzania.

Underlying support for research on gene drive-modified mosquitoes

While many participants expressed serious reservations about gene drive mosquitoes, there was an underlying consensus that research on the technology was necessary and should continue under controlled, transparent and auditable conditions. They emphasized that any consideration of GDMMs should be guided by robust, context-specific evidence, and that research is a necessary step in generating such evidence. Participants supported contained and semi-field studies, provided they were carried out transparently, in compliance with national laws, and under the supervision of competent, and independent authorities in the country. One participant elaborated this:

> *"I would be in a better position to give my opinion if I had answers to all the questions I have; if there was evidence showing how effective it will be, what risks it could cause, and what prevention and mitigation plans exist. But I understand that to get those answers, there has to be research that is specific to my settings or settings similar to mine, so I cannot oppose research."*

Several participants also made a clear distinction between "opposing field releases" and "rejecting gene drive research" altogether. They argued that without research, the critical questions surrounding GDMMs related to safety, effectiveness, reversibility, and ecological impact would remain unanswered. In this context, research was viewed not only as acceptable but as essential to informing responsible future decisions. Many advocated for a phased, cautious approach to technology development, allowing enough time to observe, learn, and adapt at each stage. When asked

how long it might take before they would feel comfortable with field releases, the participants were split in their responses. While some estimated a period of no less than 20 years, others said that they would not ever be comfortable as some ecological effects could take much longer to surface. Other participants said they would need more information about the technology to be able to make more informed estimates. One participant said:

> *"I am in support of research, to understand it, and to generate the much-needed evidence, but I oppose openly releasing them, whether for research or implementation purposes."*

Transparency, inclusivity, and national ownership were identified as key conditions for research to be credible and socially acceptable. Participants stressed the importance of involving local experts, sharing research milestones with the public, and conducting activities under a clear ethical and regulatory framework. Some expressed interest in visiting laboratories to see how containment procedures were being followed, reflecting a desire for hands-on engagement and trust-building. One participant summarized:

> *"If policies, regulations and guidelines are followed, I am in support of the research going on. I do not see why research should not go on. I would like to have all my concerns addressed, and that requires research, and therefore research must continue."*

The need for ethical and inclusive engagement

Participants strongly emphasized the need for inclusive, transparent, and democratic engagement processes, especially with communities that are most affected by malaria. They expressed concern that such communities had not been meaningfully involved in shaping the research agenda around gene drive technologies. Engagement, they argued, should not be treated as a "box-ticking" exercise or occur only at the point of implementation. Instead, it must begin early and continue throughout the research process, creating space for people to ask questions, raise concerns, and influence decisions. One participant said:

> *"No one knows about challenges with malaria more than people who live in malaria endemic settings. It is unfair to bring new things to them without asking them what they need."*

Beyond community-level engagement, participants also raised concerns about the low level of public knowledge about gene drive technologies. They noted that most citizens were unfamiliar with this technology, its potential risks, or its possible role in malaria control. In this context, they argued, expecting meaningful public input or consent would be unrealistic. Participants called for greater investment in public education, using accessible and contextually appropriate channels to ensure that people understand what is at stake. They stressed that ethical engagement should be ongoing, and must go beyond simply providing information or advocating for the technology. It should involve genuine dialogue, two-way communication, and the right to say no, ensuring that communities are not merely recipients of technology, but active participants in shaping its development and use.

Concerns about gene drive mosquitoes

The participants voiced a wide range of concerns about the introduction of GDMMs for malaria control, including: (i) uncertainties in how GDMMs function and their long-term ecological effects; (ii) lack of clarity on liability and accountability; (iii) limited transparency in research processes; (iv) inadequate local scientific capacity; (v) risks of cross-border impacts; (vi) fear of deepening technological dependency; and (vii) the marginalization of local solutions. Participants emphasized the need for context-specific evidence, transparent decision-making, and regionally grounded expertise before moving forward.

Concerns over uncertainties and unknowns

Participants expressed significant concern over the level of uncertainty surrounding GDMMs, particularly regarding their function, long-term ecological impacts, and the adequacy of current risk assessment mechanisms. They noted that even among the scientific community, there appeared to be a degree of uncertainty, which makes it difficult for non-scientific stakeholders to engage with confidence. Several participants noted that existing risk assessment tools

were not specifically designed for GDMMs, which limits their ability to accurately capture potential risks. This gap in foundational knowledge contributed to the hesitation among the CSOs, as they felt unable to form fully informed opinions or recommendations in the absence of context-specific and evidence-based understanding, as one participant explained:

> *"Even scientists are grappling in developing risk assessment, they also don't know how it works, or what adverse effects it might bring. There is still so much unknown even amongst the scientists. Current risk assessment is not even developed for gene drives, and we still do not understand risks pathways. It is challenging for me to see what to compare it with, when I do not understand what I am comparing."*

Additionally, participants emphasized that GDMMs could not be adequately compared with previous other technologies, since they are self-propagating and could persist indefinitely in the environment. This, they perceived, makes it difficult to draw direct comparisons with other interventions, especially those that can be more easily contained or reversed. While participants acknowledged the value of lessons from related fields, they cautioned against relying too heavily on such analogies in decision-making. Instead, they called for research that is specifically tailored to the unique characteristics of GDMMs, arguing that proceeding without this would pose unnecessary risks. Importantly, these concerns were not framed as opposition to research itself, but rather as a call for careful, evidence-based development. As one participant put it:

> *"Gene drives is unique, we cannot compare with other biocontrol technologies. There is no similar technology where effects of modification persist in the environment like this, so we cannot really accept findings from other projects within the same area. There is a knowledge gap."*

Concerns over lack of accountability

Participants raised critical concerns about accountability and liability, pointing out that it was unclear who would be held responsible in the event of adverse outcomes; whether it would be the developers, researchers, funders, or national governments. Participants emphasized that before any consideration of environmental release, there must be well-defined legal and regulatory frameworks that clearly outline roles and responsibilities across all stages of research and implementation. Without such safeguards, participants feared that affected communities might be left to shoulder the consequences. One participant articulated this concern:

> *"I am not saying no to the technology, but I am concerned that the liabilities on research are removed, and I worry that those researching it will not be accountable in case they cause harm to our people, or our environment. As we've seen with other technologies in the past, it is often our communities that are left to deal with the consequences and pick up the broken pieces."*

Participants further noted that, to their knowledge, no existing national or international guidelines address accountability for GDMMs specifically. This perceived regulatory gap was particularly troubling given the irreversible nature of GDMMs. As such, participants argued that GDMMs present unique and heightened risks compared to other public health interventions and should therefore be subject to exceptionally stringent governance and oversight. Participants advocated for the establishment of clear accountability mechanisms, including the assignment of responsibility for unintended effects, proactive planning for potential risks, and transparent communication of risk management plans. These systems, they argued, are necessary to protect communities and ecosystems, and to build public confidence in the research process, as one participant noted:

> *"There are no guidelines on mitigating gene drives. It is unclear what the associated risks are, how they will be mitigated, and who will be accountable for that. These mechanisms need to be put in place before we proceed any further."*

Concerns over limited transparency

Participants voiced strong concerns about a perceived lack of transparency in how GDMMs research is being conducted. Many reported that critical information was often inaccessible, not only to the CSOs,

but also to the broader public, leading to feelings of exclusion, mistrust, and suspicion. Several participants described what they perceived as a culture of secrecy, raising questions about why, if the research was safe and beneficial, the process was not being communicated more openly. For many, this perceived lack of openness suggested the possibility of hidden risks or undisclosed agendas, as one participant remarked:

> *"I am not even sure what is happening in my own country. With all this secrecy, how can I be confident that the research going on is safe? If it is safe, why hide it?"*

Participants further explained that, in the context of GDMMs, whenever stakeholder engagements have occurred, they often appeared to be driven by the need to gain acceptance or approval, rather than a genuine commitment for a two-way dialogue. As a result, some CSOs reported choosing not to participate in certain forums out of concern that their involvement might be seen as endorsement of the technology. They cautioned that continuing to sideline CSOs and restricting access to information would likely deepen public resistance, whereas a more transparent, inclusive, and participatory approach could help build trust and shared understanding, as one participant shared:

> *"We question a lot. The technology, the process, the agenda, and we want transparency. That is normally not well received, so they do what they can to keep us from getting any information, and that involves not engaging us."*

Importantly, participants clarified that transparency does not mean disclosing every technical detail. Rather, they called for the regular communication of key milestones, including emerging risks and how they are being addressed. They emphasized the need for respectful engagement, grounded in shared concern for community health and wellbeing. Altogether, participants advocated for a culture of openness, where questions and concerns are welcomed, and where civil society is seen as a partner rather than an obstacle in the responsible development of new technologies:

> *"When we ask for transparency, we do not want to know all the details, just the important milestones reached. Risks identified, and how they are being addressed. When we have questions or concerns, we would like to see those addressed. Do not treat us as enemies, we are also concerned about the health and wellbeing of our people, I believe, just as you are."*

Concerns over inadequate local expertise

All participants raised concerns over limited local expertise in GDMMs science, particularly in the areas of risk assessment, containment, and long-term monitoring. They questioned whether the country already has scientists who could competently evaluate the technology across all phases, from development and testing to release and long-term monitoring. The lack of trained, independent experts was seen as a significant barrier to informed decision-making and proper oversight, as one participant expressed:

> *"What expertise? In development? In the event that they are released? In risk assessment and mitigation? I do not believe that we have someone with expertise across all these aspects. The developers may not understand details of the sites targeted for release, and those with this knowledge may not understand the details of the technology. There is a huge knowledge gap across this sphere, and it worries me."*

While most participants supported the idea of capacity building, they insisted that training should be conducted by neutral parties, not by the developers of the technology themselves. They argued that allowing developers to train local experts could create conflicts of interest, potentially leading to biased knowledge transfer. Instead, they recommended using models of independent training, such as those employed under the Convention on Biological Diversity (CBD) (Prip 2018), which bring in experts from a range of institutions to provide balanced and objective perspectives. They believed this approach would enhance national sovereignty and reduce reliance on external actors, as this participant elaborated:

> *"Building of expertise is important, but who is building it? We need independent experts who can understand the risks and mitigate them. But if they are trained by those who are developing the technology, then there is a conflict of interest in this case, because the developers want*

their technology to spread, and may therefore not be open about some risks, or may not know what potential risks are."

Participants referenced past experiences with training workshops that had been facilitated by the CBD as a positive model. These sessions were described as having been inclusive, transparent, and objective, bringing together stakeholders from across sectors and countries to learn about biosafety, detection, and monitoring of genetically modified organisms (GMOs). Participants recommended that such approaches be adapted for GDMMs, helping to ensure that future regulatory decisions are grounded in credible and impartial expertise. One participant recalled the training they had participated in saying:

"In the CBD detection and monitoring workshop, we were trained by independent developers, a team of them from across different institutions. There was objectivity in the training, and no advocacy for one technology or the other. I learned quite a lot"

Concerns over transboundary issues

Participants highlighted the importance of considering the regional implications of GDMMs releases, particularly due to their self-propagating nature. They emphasized that once released; GDMMs could easily cross national borders, potentially affecting neighboring countries without their consent. Given Africa's shared ecological zones, participants argued that decisions about environmental release cannot be made in isolation. Instead, they called for regional consensus and engagement with all potentially affected countries, as one participant noted:

"We will need to ensure that there is consent across all neighboring countries, to make sure that they understand what they are subjecting their people to, directly or indirectly.

To address these concerns, participants recommended strict adherence to international protocols, such as the Cartagena Protocol on Biosafety and the CBD, both of which provide guidance on the transboundary movement of GMOs (Prip 2018; Convention on Biological Diversity 2000). They stressed that these agreements must be upheld not only in principle, but also in practice, by including clear provisions for liability and coordinated oversight. Participants warned that without regional collaboration and shared decision-making, the release of GDMMs in one country could unintentionally put neighboring countries at risk, as these two participants explained:

"When dealing with international protocols, our neighbors are party to those protocols, and we should put strict liability, and need to apply those for the neighboring countries."
"Look at COVID-19, just one mistake made in one country, and the whole world paid the price. I would rather we not be put in such situation, especially if we are left to deal with the aftermath ourselves."

Concerns over dependency and technological neo-colonialism

Participants voiced strong concerns that Africa, and Tanzania in particular, is being positioned as a testing ground for technologies developed and funded by actors from the more developed countries. They felt that key decisions regarding the research and deployment of GDMMs were often made outside the continent, often without adequate considerations for local priorities, values, or systems of accountability. Several participants described this dynamic as a form of technological neo-colonialism, where power over innovation remained concentrated in the hands of international stakeholders, as this participant elaborated:

"Africa is in a subordinate position. If all decisions are made outside of Africa, how can we say we are respected? We know that we cannot change the system, but we can push for reform in the system."

Concerns about deepening dependency surfaced throughout the discussions, as participants warned that if GDMMs were adopted without meaningful local control, countries like Tanzania could become increasingly reliant on external institutions for technical expertise, financial support, and decision-making authority. These concerns were grounded in past experiences in both the agriculture and health sectors, where they felt that externally-led solutions had contributed to long-term disempowerment and limited national ownership. Participants emphasized the need

to build and prioritize locally driven alternatives that reflect regional realities and capacities:

> *"Dependency is not caused by just one thing. When we talk about dependency, it is not in just malaria, it could also be in so many other areas too. We need to understand what both direct and indirect effects of this technology could be. What other unintended effects of this technology could drive us into dependency?"*

Several participants further emphasized that the region's current dependency on donor funding for malaria control should not be used to justify the adoption of GDMMs. They argued that framing GDMMs as cost-saving was misleading, especially given that the technology would not replace existing interventions. Instead, they speculated it would likely add to the overall cost of malaria control, requiring ongoing resources for implementation, monitoring, and regulation. In this way, participants expressed concerns that GDMMs could deepen dependency rather than reduce it, by introducing another layer of reliance on foreign funding, expertise, and infrastructure:

> *"The fact that we are so dependent in donor funding for malaria is not a good enough justification for this technology. Remember that this is not a silver bullet, so we will still need to rely on the other malaria control approaches, so in this case, it will just be adding on to the cost, hence adding on to the dependency."*

To underscore their concerns, participants cited examples of similar dependency patterns. A frequently referenced case was genetically engineered insect-resistant cotton (Bt cotton) (Perlak et al. 1990), which is modified with a *Bacillus thuringiensis* gene to produce toxins against key pests but has also raised issues of farmer dependency and sustainability in countries such as South Africa and Burkina Faso. According to the study participants, the Bt cotton was introduced with high expectations in vulnerable farming communities but instead of improving livelihoods, the value of cotton fell, production costs rose, and many farmers were left worse-off. For the participants, this served as a powerful warning about the dangers of over-reliance on external technologies:

> *"For example in South Africa, Bt. Cotton promised huge returns, was given to the poorest, but when GM cotton was introduced the cotton value dropped. The farmers became more dependent and got into more debt, and were left more destitute. Dependency on just one technology is really risky, for the people, and governments too."*

Concerns over neglect of local solutions

A recurring theme across interviews was the view that current, proven malaria interventions had not yet been fully deployed or optimized. Participants questioned why more investments were not being directed toward improving access to ITNs, IRS, and larviciding strategies, especially when these were well understood and already accepted by communities. They argued that the rush to GDMMs overlooked the potential of scaling up what already works.

In addition to conventional strategies, participants highlighted the need to value and invest in locally developed solutions, including indigenous knowledge systems and biolarvicides created within African countries. Participants noted that these approaches have received far less attention or funding, despite their alignment with local realities and community acceptance. Several participants perceived the current push for GDMMs as being driven more by foreign interests and the appeal of cutting-edge technology, than by a commitment to sustainable malaria elimination. They stressed the importance of building upon tools that communities already trust and understand, rather than overlooking homegrown interventions in favor of experimental ones, as one participant explained:

> *"We have our own biolarvicides, but we are not even using them as we should. If the interest was really to eliminate malaria, why not focus on the locally generated solutions, that we already know work?"*

Discussion

This study explored the perspectives of Tanzanian CSOs on the use of GDMMs for malaria control. Overall, the participants expressed a cautious yet engaged position, supporting the generation of locally grounded evidence through research, while strongly

advocating for a delay in environmental release until certain critical conditions are met. A summary of the participants' insights and recommendations is provided in Table 1. While participants acknowledged the potential of GDMMs' contribution to public health goals, their views were shaped by significant concerns related to scientific uncertainty, safety, accountability, limited local capacity, and the broader risks of technological dependency. These findings align with previous research that emphasize the importance of broad societal engagement, especially in contexts where the technology is novel and potentially irreversible (Bofu et al. 2023; Hartley et al. 2021; Okorie et al. 2014). In this study, however, the participants expressed a firmer stance than other stakeholder groups, clearly stating that they could not support the development or release of GDMMs unless credible evidence was provided to address their specific concerns. Importantly, these reflections are situated in the Tanzanian context and should not be assumed to represent the views of CSOs across Africa.

One of the most prominent concerns expressed by the participants was the limited scientific understanding surrounding GDMMs, even among the scientific community. This perceived knowledge gap, they argued, contributes to growing skepticism among other stakeholders who depend on local experts to guide responsible decision-making. Similar concerns have been raised by a wide range of stakeholders across Africa, echoing the existing literature that underscores the persistent scientific uncertainties related to GDMMs (Finda et al. 2023; Hartley et al. 2021; Okorie et al. 2014). There have been efforts to bridge this knowledge gap, such as the WHO and NASEM's guidance frameworks for testing genetically modified mosquitoes (National Academies Press 2016; World Health Organization 2021), the Cartagena Protocol on Biosafety which provides an international basis for precautionary risk assessment and transboundary governance of living modified organisms (Convention on Biological Diversity 2000), CBD's new guidance for risk assessment of gene drive modified mosquitoes (Convention on Biological Diversity 2024), and NEPAD's acknowledgment of the importance of gene drive regulation and capacity building (AUDA-NEPAD. 2024).

A key recommendation from the discussions was the urgent need to strengthen national capacity to understand, assess, and monitor gene drive technologies. Participants underscored that without such capacity, national actors risk remaining dependent on external experts and developers, thereby limiting their ability to make sovereign and well-informed decisions. To mitigate this, they highlighted the importance of training initiatives that are independent of technology developers and their funders, pointing to the examples piloted under the CBD, which were perceived as inclusive, objective, and capable of fostering legitimate decision-making process (Prip 2018). This emphasis aligns with global guidance that capacity building in low- and middle-income countries should be undertaken transparently and independently, in order to safeguard against conflicts of interest and ensure long-term credibility (Prip 2018; Abdi et al. 2024). Despite the consensus on its importance,

Table 1 Summary of concerns and suggested solutions as recorded during the discussions with the CSO representatives[+]

Concern identified	Recommendations proposed
Uncertainties surrounding GDMMs	Invest in local, context-specific research to generate evidence and close knowledge gaps
No frameworks for RA for GDMMs	Develop context-specific GDMMs-specific risk assessment tools and pathways
Lack of accountability mechanisms	Establish clear legal and regulatory frameworks that define liability and redress
Limited local expertise	Build independent national capacity through transparent, non-developer-led training
Limited transparency	Ensure regular, transparent communication of research milestones and emerging risks
Transboundary effects	Secure regional consent and coordinate through international biosafety protocols
Technological dependency	Prioritize locally developed solutions and ensure decision-making autonomy
Neglect of current malaria interventions	Strengthen and scale up current malaria control strategies before introducing new tools
Limited public engagement	Conduct inclusive, early, and ongoing public education and dialogue
Premature field release	Ensure long-term monitoring in contained and confined settings before field releases

[+]These concerns were raised by the CSOs during the discussions. And the recommendations were also suggested by the CSOs[+]

participants expressed concern over the absence of strong national leadership in convening or coordinating such initiatives, a gap that has also been raised by experts in the field (Abdi et al. 2024; Rabitz 2019). While there was no clear agreement on which institution should assume this role, participants observed that governments have thus far played only a limited role in supporting or facilitating capacity-building efforts.

Encouragingly, efforts are underway across Africa to strengthen the capacity needed to understand, monitor, and regulate GDMMs. A notable milestone was the successful production of the first genetically modified mosquito in Africa, a joint achievement by Tanzanian scientists at the Ifakara Health Institute (IHI) and researchers from Imperial College London, which demonstrated the region's growing entomological and molecular expertise (Africa 2024). Regional organizations such as AUDA-NEPAD and The East African Science and Technology Commission (EASTECO) are also assuming more proactive roles in championing ethical standards, promoting transparency, and building regional momentum toward trustworthy governance (AUDA-NEPAD. 2025, 2024; Pan African Mosquito Control Association 2023). In parallel, several Africa-based initiatives are contributing to improved technical and governance capacity. In Tanzania, IHI has hosted a series of masterclasses on gene drives, bringing together global experts and African malaria leaders to strengthen local scientific literacy and policy dialogue (Institute et al. 2023, 2021). The Pan-African Mosquito Control Association (PAMCA) has also, for nearly a decade, organized short courses on gene drives for African scientists and regulators (Pan African Mosquito Control Association 2023). Other efforts include a series of Tanzanian-led short courses on gene editing for African bioscience professionals (Available from 2025), and efforts by the African Genetic Biocontrol Consortium, which regularly convenes trainings workshops on regulation, governance, monitoring, and communication, aiming to cultivate diverse capacity across multiple sectors (African Genetic Biocontrol Consortium 2025).

Collectively, these initiatives demonstrate a growing but still developing foundation for capacity building, underscoring the need for stronger coordination, government ownership, and sustained investment to ensure long-term effectiveness. However, a major challenge is that these efforts remain largely invisible outside research and regulatory circles. Raising broader awareness of these milestones is critical not only to showcase that national and regional capacity is steadily advancing, but also to reassure stakeholders and communities that Africa is equipping itself to manage this technology responsibly.

Another prominent concern related to accountability and transparency in GDMMs research and governance in Tanzania. Participants stressed that currently there were no clear mechanisms in place to determine who would be held responsible in the event of adverse outcomes related to gene drive technologies in the country. While the environmental management framework has recently been updated through regulations on access and benefit sharing and the right to compensation (United Republic of Tanzania 2024), these instruments do not directly address the unique risks and governance needs of GDMMs, reinforcing participants' concerns about the absence of specific provisions for assigning accountability or managing potential unintended consequences. Such concerns are consistent with previous research highlighting the lack of comprehensive liability frameworks and the ambiguity of governance responsibilities as major barriers to building public trust and ensuring the ethical acceptability of GDMMs (Resnik 2015, 2017; Kuzma 2023). Participants also drew attention to past experiences in Africa where externally introduced technologies failed to deliver on their promises, ultimately leaving communities more vulnerable (Scoones 2009; Pan African Visions 2025). These historical instances were seen as cautionary tales, reinforcing the view that African governments must learn from the past and take extra care not to expose already marginalized populations to unnecessary risks.

In this regards, while the Cartagena Protocol on Biosafety offers some guidance on liability, redress, and state responsibility in the context of living modified organisms (Convention on Biological Diversity 2000), participants critiqued that it does not provide specific or detailed provisions for novel technologies such as GDMMs. This partial coverage highlights both the relevance and the limitations of existing international frameworks. On one hand, the Protocol establishes important principles, such as the precautionary approach and the need for liability mechanisms, that could inform GDMM governance. On

the other hand, its lack of explicit guidance on gene drive applications means that additional normative and regulatory work is needed to clarify lines of accountability, define liability in the case of transboundary harms, and ensure that responsibilities are not left ambiguous (Convention on Biological Diversity 2000). Participants argued that without such clarity, there is a risk that responsibility could default to affected communities, who are least equipped to manage potential harms. They therefore called for governments, in collaboration with regional and international bodies, to expand on existing biosafety provisions under the Cartagena Protocol and develop context-specific mechanisms for GDMMs that ensure transparent governance, fair distribution of responsibility, and effective protection for vulnerable populations.

While acknowledging the potential of GDMMs, participants emphasized the importance of balancing external innovation with deliberate investments in local scientific capacity, regulatory preparedness, and sovereign decision-making structures. This concern, that most biocontrol technologies such as gene drives are developed and funded by institutions based in high-income countries, has been flagged as one that may potentially result in unequal power dynamics in contexts where governance systems and technical expertise are still evolving (Kormos et al. 2022; Delborne et al. 2018). Interestingly, several predictions have been made about the potential of GDMMs to lower dependency on donor funding, particularly because of their self-propagating nature, which enables them to spread through target mosquito populations without the need for repeated external inputs (James and Santos 2023; James et al. 2023). The participants cautioned that self-propagation could, paradoxically, deepen dependency by requiring long-term reliance on external scientific institutions for monitoring, evaluation, and decision-making. In addition, they worried that the same self-spreading capacity could accelerate the spread of unintended negative effects, which might place Tanzania at greater risk and cost in trying to mitigate them.

Participants in this study did not reject international support outright; rather, they advocated for a more equitable and inclusive approach, in which local efforts, public health priorities, and community knowledge are taken into consideration, and are meaningfully integrated into research design, field testing, and long-term governance. This sentiment echoes broader ethical literature that warns against the risk of deploying emerging technologies in politically or economically vulnerable regions without adequate consultations or capacity building (Schroeder et al. 2018; Resnik 2018; Roberts et al. 2024; Emerson et al. 2017). Scholars in this field emphasize the importance of aligning private interests with the public good. Achieving this requires a commitment to equity, justice, and transparency at every stage of gene drive research and development. Crucially, it also means treating affected communities as equal partners in shaping technologies intended to serve them (Roberts et al. 2024; Emerson et al. 2017).

Although several modeling studies have demonstrated the potential cost-effectiveness of GDMMs for malaria control (Metchanun et al. 2022; Leung et al. 2022; Hancock et al. 2024), participants expressed caution in drawing firm conclusions before real-world evidence on efficacy and long-term impact becomes available. They emphasized that, while modeling provides valuable projections, implementation is likely to add to existing malaria control costs rather than fully replace current strategies. This perspective aligns with broader literature on the introduction of novel public health technologies, which cautions that cost-effectiveness in models may not capture the full operational, regulatory, and social costs associated with real-world deployment (Metchanun et al. 2022; White et al. 2011).

Participants recommended that cost–benefit assessments for GDMMs take into account not only projected savings, but also the full range of added costs, such as long-term monitoring, regulation, public engagement, capacity building, and potential unintended consequences. This aligns with economic evaluation frameworks in global health that stress the inclusion of both direct and indirect costs, as well as the consideration of long-term sustainability and uncertainty in outcomes (Jamison et al. 2013; Walker and Fox-Rushby 2000; Drummond et al. 2015). Participants further highlighted the importance of evaluating these costs across both short-term and long-term horizons, ensuring that economic models reflect the complex realities of integrating GDMMs into national malaria control programs.

Despite the concerns, participants expressed their support for continued research on GDMMs, emphasizing the importance of generating locally relevant

evidence to inform future decision-making. They viewed research as a critical tool for understanding the technology's potential, and for identifying and addressing context-specific risks and developing appropriate mitigation strategies. This perspective resonates with broader literature that highlights the importance of empirical field data to complement modeling studies, particularly for emerging technologies where uncertainty about ecological, social, and health impacts remains high (National Academies Press 2016; World Health Organization 2021). Participants' support, however, was conditional. They consistently emphasized the need for clear laws, regulations, and ethical guidelines to govern how research is conducted, and to ensure accountability throughout the process. Although Tanzania has established regulations for research involving GMOs and living modified organisms (LMOs) (United Republic of Tanzania 2024; National Biosafety Authority 2015, 2009), participants expressed dissatisfaction with this, noting that the regulatory status of gene drives remains ambiguous, particularly in the context of public health applications. They therefore called for the development of gene drive–specific guidelines and oversight mechanisms. These perspectives and recommendations reflect a strong alignment with the precautionary principle, calling for preventive action in the face of uncertainty, shifting the burden of proof to technology developers, and prioritizing safer alternatives where available (Hartley et al. 2022; Kriebel et al. 2001). Moreover, the support for research was not unique to the CSOs, it has also been reported by previous studies across Africa (Finda et al. 2023), and including country-level research in Mali (Marshall et al. 2010), Nigeria (Okorie et al. 2014), Uganda (Hartley et al. 2021) and Tanzania (Finda et al. 2020, 2021), all calling for context-specific evidence.

Participants in this study favored a phased approach in researching GDMMs. However, nearly all participants strongly opposed any field trials of GDMMs, without first ensuring that robust systems and sufficient national capacity were in place to monitor, regulate, and mitigate potential risks. They insisted on the need for comprehensive long-term evidence on GDMMs' efficacy and safety, generated through rigorous containment and confinement studies. When asked what constituted *"long-term,"* participants gave varied and often speculative responses, generally preferring to wait and see the outcomes of extended laboratory testing before forming definitive views. This ambiguity reflects a broader gap in global guidance.

To our knowledge, there is no universally accepted standard for how long laboratory research on gene drives should continue before progressing to semi-field or field stages. Instead, gene drive developers have largely followed individualized research pathways. A critical question raised by these discussions is whether it is even feasible to establish generalized timelines for GDMM research across the different phases of development. The consensus in the literature suggests that while stepwise, phased approaches are essential, fixed timelines are unlikely to be realistic due to differences in types of GDMMs, local ecological dynamics, regulatory contexts, and capacity levels (National Academies Press 2016; World Health Organization 2021; James et al. 2018). In practice, this means that the progression from laboratory to confined field studies and eventually to open releases may vary significantly between countries and projects. The duration of research before any potential field release could span many years, depending on both scientific uncertainties and socio-political considerations. Consequently, most global guidance advocates for a case-by-case determination of timelines, anchored in rigorous, context-specific risk assessments, as well as regulatory approval processes (National Academies Press 2016; World Health Organization 2021; Esvelt and Gemmell 2017). For example, risk assessments may highlight uncertainties that require extended laboratory testing in some settings, while in others, sufficient evidence and oversight could justify earlier progression. While such flexibility prioritizes safety, it also underscores participants' concern that field releases may take longer and remain more uncertain than often anticipated.

In this study, we observed limited awareness among CSOs of existing global guidelines, such as those developed by WHO and NASEM (National Academies Press 2016; World Health Organization 2021), which already emphasize phased research, strong regulatory oversight, and safety as prerequisites for progression. Many of the concerns raised by CSOs on timelines, safeguards, and accountability are in fact anticipated and addressed within these frameworks, although this information has not reached them effectively. To address this limited awareness, we recommend that efforts to ensure ethical research

and development of GDMMs, including adherence to phased guidance from WHO, NASEM, and other global bodies, be made visible to the public, and particularly to community advocacy groups. Similarly, national initiatives to strengthen regulatory preparedness and safety oversight should be communicated more openly to help build greater public confidence that safety is a priority both globally and within countries.

Regarding public and community engagement, participants were united in calling for more inclusive, transparent, and ongoing dialogue. They emphasized that ethical engagement must move beyond consultation, towards participatory decision-making that reflects community priorities and values. This recommendation is strongly echoed in the literature, which cautions that engagement efforts perceived as superficial or performative can undermine trust, provoke resistance, and ultimately jeopardize the success of even the most well-intentioned public health interventions (Resnik 2018; Hartley et al. 2019; Lavery et al. 2010). Debates on the timing and modalities of engagement remain active both within and outside Africa. While some stakeholders argue for early and continuous dialogue with communities and the public, others suggest postponing engagement until the technology is more mature and uncertainties have been resolved (Finda et al. 2023). Despite these differences, there is broad agreement that engagement should be aligned with country-specific governance structures and guidelines (Finda et al. 2023). Several initiatives are already underway in this area, including the Gene Drive Outreach Network (Available from 2025), AUDA-NEPAD (AUDA-NEPAD. 2024), and the GeneConvene Virtual Institute (GeneConvene Virtual Institute 2025), all of which host discussions, training sessions, and online activities to broaden awareness. In addition, GDMM developers maintain public websites where they share research updates and engagement materials. However, these initiatives often remain concentrated in policy and expert spaces. A critical next step is to ensure that such efforts reach grassroots and community-representative groups, so that those most affected by malaria, and most central to the ethical acceptability of GDMMs, are meaningfully included in shaping decisions about the technology.

This study had several limitations that should be considered when interpreting the findings. Firstly, while participants were purposefully selected for their active involvement in biosafety and biotechnology policy dialogues, the sample included only ten of the 55 TABIO member organizations, and may not fully capture the breadth of perspectives across the entire alliance or the broader civil society landscape in Tanzania. Secondly, the focus on individuals already engaged in national or regional discussions on biocontrol technologies and in some cases GDMMs may have introduced a degree of bias toward more informed or opinionated voices, potentially excluding less-engaged but equally relevant perspectives. Additionally, while the combination of FGDs, IDIs, and multi-stakeholder discussions strengthened the depth of insight, the small sample size limits the generalizability of the findings beyond this group. With this said, this study still offers an in-depth and timely understanding of the perspectives of a stakeholder group that is often overlooked or avoided in biotechnology discourse, but that is still very close to the government and communities and has a power to potentially affect any progress made in research and development of GDMMs. It is also important to note that most of the concerns expressed by the CSOs in this study have also been flagged internationally, also by those supporting these technologies, and efforts are ongoing to address them. It is crucial to ensure that these efforts are made known to the communities in malaria endemic settings, and the CSOs, to help reduce the anxiety that may be associated with the concerns. Altogether, the insights captured here offer valuable contributions to the broader conversation on the governance, ethics, and social dimensions of emerging vector control technologies.

Conclusion

This study highlights the critical role that CSOs play in shaping the discourse on emerging technologies such as GDMMs for malaria control. While the participating CSO representatives acknowledged the urgency of tackling malaria and expressed openness to continued research, they also voiced deep concerns about the safety, accountability, transparency, and long-term implications of gene drive technologies. Their perspectives reflect a cautious yet constructive approach, closely aligning with the elements of the precautionary approach. It is important to stress that

even in a single country, CSO views are not uniform, but rather reflect a spectrum of positions informed by diverse experiences and constituencies. This diversity should not be seen as a barrier, rather as a valuable asset in creating balanced, inclusive, and ethically grounded policies. The perspectives captured in this study offer essential guidance for national and regional decision-makers, highlighting the need to prioritize community engagement, provide timely and accessible research updates, build local capacity, and avoid one-size-fits-all solutions in the governance of high-stakes technologies.

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Authors' contributions MFF was involved in study design, data collection, entry and analysis, interpretation of the results and writing the manuscript. FOO and MS were involved in study design, supervision and critical revision of the manuscript. MS, RN, GM and SS were also involved in data collection and entry. All authors read and approved the final manuscript.

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Data availability All data for this study will be available upon request.

Declarations

Conflcit of interests The authors declare no conflict of interests.

Ethical approval Ethical approvals for this project were obtained from Ifakara Health Institute's Institutional Review Board (Protocol ID: IHI/IRB/No: 2-2021) and the Medical Research Coordinating Committee (MRCC) at the National Institute for Medical Research (Protocol ID: NIMR/HQ/R.8a/Vol.IX/3804). Permission to publish this study was obtained from NIMR, ref: BD.242/437/01C/151.

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