Opinions of key stakeholders on alternative interventions for malaria control and elimination in Tanzania

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Abstract

Background

Malaria control in Tanzania currently relies primarily on long-lasting insecticidal nets and indoor residual spraying, alongside effective case management and behaviour change communication. This study explored opinions of key stakeholders on suitability and potential of six alternative vector control interventions for supplementing ongoing malaria control and elimination efforts in Tanzania.

Methods

Focus group discussions were held with policy-makers, regulators, research scientists and community members, each group having 6-10 participants. Alternative interventions discussed included: a) improved housing, b) larval source management, c) mass drug administration (MDA) with ivermectin to reduce vector densities, d) modified mosquitoes including genetically-modified or irradiated mosquitoes, e) targeted spraying of mosquito swarms, and f) spatial repellents. Discussions focused on stakeholder opinions on comparative value of these interventions for supplementing efforts towards the 2030 malaria elimination target.

Results

Larval source management and spatial repellents were widely supported across all stakeholder groups, while insecticide-spraying of mosquito swarms was least preferred. Support for MDA with ivermectin was high among policy makers, regulators and research scientists, but encountered opposition among community members due to perceptions that it requires significant efforts and compliance. Community members expressed strong desire and support for programmes to improve housing for poor people in high transmission areas, while policy makers challenged sustainability of this strategy given its high costs. Techniques of mosquito modification, specifically those involving gene drives, were viewed positively by community members, policy makers and regulators, but encountered high degrees of scepticism among scientists. Overall, policy-makers, regulators and community members trusted scientists to provide appropriate advice for decision making.

Conclusion

Stakeholder opinions regarding alternative malaria interventions were divergent, except for larval source management and spatial repellents for which there was universal support. MDA with ivermectin, house improvement and modified mosquitoes were also widely supported though each faced concerns from at least one stakeholder group. While policy-makers, regulators and community members all noted their dependence on scientists to make informed decisions, their reasoning on benefits and drawbacks of specific interventions included factors beyond technical efficiency. This study suggests the need to encourage and strengthen dialogue between scientists, policy makers, regulators and communities regarding new interventions.

Background

The World Health Organization's Global Technical Strategy for Malaria was aimed at reducing malaria incidence and mortality by 90% worldwide by 2030, and to eliminate malaria in 35 countries by the same year (1). Tanzania is one of the countries currently pursuing malaria elimination by 2030, and has witnessed significant gains since 2000 (2). To achieve this ambitious goal, the National Malaria Control Programme (NMCP) has a strategy to ensure adequate coverage of vector control interventions, primarily the use of long-lasting insecticide-treated nets (LLINs) and indoor residual spraying (IRS) (2). The strategy also includes improved malaria diagnosis and case management, as well as roll-out of new complementary interventions where there is sufficient local evidence for impact (2). This strategy however faces multiple challenges, including widespread mosquito resistance to insecticides (3,4), tendency of some vector populations bite people outdoors or earlier in the evenings (5,6), high costs and sub-optimal compliance among users (7).

Several complementary vector control interventions have been proposed as possible candidates to accelerate the malaria elimination efforts (8). Examples include: a) larval source management (LSM) (9,10), b) topical repellents for personal protection (11,12), c) mass drug administration with endectocides such as ivermectin (13,14), d) use of genetically-modified mosquitoes, currently under development (15–17), e) outdoor targeting of malaria mosquitoes e.g. through insecticide-spraying of mosquito swarms (18–20), f) housing improvement measures such as window screening and improved house designs (21–23), g) spatial repellents, which protect multiple people over wide areas (24,25), h) attractive toxic sugar baits, which target sugar-seeking mosquitoes (26,27) and i) mosquito-killing fungal spores and toxins(28,29).

Unfortunately, most of these interventions still do not have adequate evidence to support deployment at scale. Instead, significant investments, as well as strong multi-sectoral collaborations are still needed to complete their development and evaluation. Moreover, to ensure that these potential alternative interventions meet user needs and are sustainable, it is crucial to consider, early on in their development, the views and opinions of the key stakeholders. This study therefore explored opinions of key stakeholders regarding suitability and potential of six alternative vector control interventions, which could be used to supplement malaria elimination efforts in Tanzania.

Methods

Study site and stakeholder selection

This study was done in Tanzania between December 2018 and May 2019, and involved four groups of stakeholders, namely: a) policy-makers, b) regulators, c) research scientists and d) community members. The stakeholders were all involved either directly or indirectly in malaria control in Tanzania. The study was designed to capture differences in opinions, and to elucidate arguments that explain respective stakeholder positions.

Research scientists were selected from two leading research institutes in the country: Ifakara Health Institute (IHI) and National Institute for Medical Research (NIMR), and included persons working on malaria control strategies in Tanzania. The group included entomologists, economists, health systems and policy researchers, molecular biologists and ethicists. Policy-makers on the other hand included senior officials from government ministries located in Dodoma, Tanzania's administrative capital. Participants in this group were selected from seven government ministries with direct or indirect influence on malaria control activities. These included a) Ministry of Health, Community Development, Gender, Elderly and Children, b) Ministry of Education and Vocational Training, c) Ministry of Agriculture, d) Ministry of Livestock and Fisheries Development, e) Ministry of Water and Irrigation, f) Ministry of Housing and Infrastructure and g) President's Office-Regional Administration and Local Government. Regulators on the other hand included officials from the Tanzania Medicines & Medical Devices Authority, Tanzania Commission for Science and Technology, and National Environmental Management Committee.

Lastly, community members were comprised of local community leaders drawn from ten wards in Ulanga and Kilombero districts in the Kilombero valley, in south-eastern Tanzania, where residents are mostly subsistence farmers, pastoralists or small business owners. Malaria prevalence in these areas is highly heterogeneous ranging from < 1% in the urban and peri-urban sites to > 40% in some of the villages (Swai et al unpublished) and transmission intensities also varying from < 1 to ~ 20 infectious bites per person per year (30,31).

Study procedures and interventions evaluated

Focus Group Discussions (FGDs) were used to explore opinions of the stakeholders on suitability and potential of alternative interventions that are either available or are currently being evaluated for malaria elimination in Tanzania. The alternatives assessed included: a) improved housing, b) larval source management, c) mass drug administration (MDA) with ivermectin to reduce vector densities, d) modified mosquitoes, including genetically-modified such as those with gene drives or irradiated mosquitoes, e) targeted spraying of mosquito swarms, and f) spatial repellents. All of these have previously been proposed as potential complementary interventions towards malaria control and elimination in different settings. Table 1 shows basic summaries on these interventions, including evidence on potential for each.

A total of eight FGD sessions, two per stakeholder group, were conducted, each with 6–10 participants. During the FGDs done with community members, men and women were separated to maximize participation of women, based on previous experiences (32). This separation was considered unnecessary for the other stakeholder groups. To avoid framing the discussions narrowly, a semi-structured discussion guide was used. Participants were first asked open-ended questions about their opinions on the country's progress towards malaria elimination, their views on the effectiveness of current malaria control interventions, and the need for alternative interventions for malaria control. The

facilitator then presented a brief overview of the alternative interventions for malaria elimination, by way of PowerPoint slides. The presentation was followed by participants' discussions of the interventions.

The discussions were done in Swahili (the main language spoken in Tanzania). The sessions lasted 120–150 minutes each and were audio-recorded with consent from participants. Additionally, detailed notes were taken during the discussions

Table 1

Descriptions of alternative interventions to complement ongoing malaria control and elimination efforts, as discussed with key stakeholders in Tanzania.

Intervention	Description
Improved housing	House improvement as malaria control intervention involves mosquito-proofing houses to limit mosquito entrance into the house (22,33). General housing improvement was used as supplementary components in the malaria elimination strategies in developed countries (34). In developing countries, simple modifications like screening windows and doors and closing eave spaces have resulted in a 50% decline in entomological inoculation rates (35). In Tanzania for example, housing improvement was linked to significant historical declines of Malaria in Dar es Salaam (36), and was likely a major factor in more than 99% decline in Malaria in Ifakara town (30).
Larval source management	Larval source management (LSM) refers to environmental manipulations to target mosquito larval habitats (9). LSM can include the use of larvicides as well as environmental management methods (9,10,37). In Tanzania, a large scale coverage of larviciding resulted in 21% reduction in malaria prevalence in Dar es Salaam between 2006 and 2008 (38). The Tanzanian government is currently conducting targeted larviciding in urban and rural settings as a means to speed up the malaria elimination agenda (39).
Mass drug administration of ivermectin	Ivermectin is an anthelminthic drug commonly used to control parasitic nematodes in humans and animals (40). It has been extensively used in mass campaigns for elimination of lymphatic filariasis and onchocerciasis in Tanzania (41,42). Ivermectin has been increasing in popularity as a malaria control tool; it significantly reduces female mosquito fecundity and survival when mosquitoes blood-feed on hosts that have taken ivermectin (14,40,43).
Targeted spraying of mosquito swarms	Male mosquitoes aggregate in swarms as they compete for attention of female mosquitoes searching for mating partners (44). Swarms usually occur at approximately the same time, usually at sunset, and repeatedly at same locations throughout the year (44). Studies done in Burkina Faso and Tanzania have shown that Anopheles mosquito swarms can be easily identified and targeted, and are effective for reducing overall mosquito density (18,19,45).
Modified mosquitoes	This intervention involves alterations of mosquito genes or physiology for the purpose of reducing their competence in diseases transmission. The modified mosquitoes are released in the environments so that they can interbreed with the wild mosquitoes and either transform them from disease-vectors into harmless mosquitoes, or to eliminate their population. Interventions currently under study include Sterile Insect-technique (SIT), which relies on irradiation of mosquitoes to make them sterile (46), genetic sterilization of mosquitoes (47) and use of gene drive systems, which spread traits of lethality or refractoriness in mosquito population (i.e. population suppression or replacement) (15,48,49). While there are currently no field studies or historical evidence of effectiveness of this technology, laboratory studies and mathematical models indicate promising results (50).
Spatial repellents	Spatial repellents (SP) prevent host-seeking mosquitoes from entering areas with the treatment, usually in form of vapor-phased active ingredients, limiting contact between humans and mosquitoes (24). SP include botanical and pyrethroid compounds such as citronella, transfluthrin and metofluthrin (24,51,52). They can be delivered in different formats, such as mosquito coils, repellent-treated clothing, repellent sandals (Finda et al unpublished), kerosene lamps (53) and eave ribbons (24,25,54). Compared to widely available topical repellents, SP can provide long-lasting repellency, requiring minimal participation from the users.

Data processing and analysis

Audio recordings of the FGDs were transcribed immediately following the discussions, then translated from Swahili to English language. Field notes were incorporated in the written transcripts as additional data. The final transcripts were reviewed in detail then imported to Nvivo 12 Plus software (55) for further processing and analysis. Deductive analysis was used to categorize codes based on the FGD guide, which explored participants' opinions on: a) the country progress towards malaria elimination, b) potential and limits of current interventions for malaria elimination, c) need for alternative approaches and techniques to support elimination efforts, d) merits and limitations of the alternative interventions, and e) their potential applications as complementary interventions in the efforts towards the 2030 malaria elimination target. Guiding quotes from participants were used to support the themes.

Results

Opinions on progress towards malaria elimination in Tanzania

Research scientists, regulators and policy makers discussed the progress made by Tanzania towards malaria elimination in terms of declining malaria prevalence as observed during the past decade. On the other hand, community members discussed the progress in terms of their daily life experiences.

Two major arguments emerged within this theme. On the one hand, it was agreed that the country had made good progress and was on the right track. On the other hand, it was also noted that the progress was slow and inadequate for elimination by 2030 as planned. Participants who emphasized that the country was on track referred to the significant reduction in malaria prevalence over the past decade, particularly noting that malaria has reduced by more than 50% since 2000. For example, one policy maker stated, "*Of course we have come far from when prevalence was as high as 20% in the whole country. Back then when you look at the map it was all red, all red I tell you. There was malaria everywhere. But now you can see quite a lot of places that have prevalence of less than 1%, so when I see that I know that we are doing well.*" (Female, Policy maker).

For community members, their idea of progress was informed mostly by their lived experiences. For example, they noted that the frequency and severity of malaria has greatly declined over the years, noting that unlike in the past when malaria infections were very frequent, several months could now go by without their children getting sick. Even when they did get sick, it was more likely not to be malaria. As one participant said, "*Ten years back there was a lot of malaria. During that time, every time you did not feel well and went to the hospital you would be told that you have malaria. Kids were getting sick very often. But now we can go for even six months without our children getting sick or needing to go to the hospital. And when we do go we hear about other diseases like urinary tract infections or typhoid. So then I know that malaria is not a big disease like it used to be.*" (Female, Community member).

There was also a group of participants who argued more cautiously that while there has been some progress, it is too slow, and does not reflect the amount of effort that the country has put in place. They also noted that the decline in malaria prevalence is not uniform across the country. As one policy maker reported, *"I think we are doing well, but not as well as I would like. As a country we have put a great deal of efforts to finish off this disease, but I am sad to see that there are areas in the country where prevalence is as high as 40%. We should not be in a situation like this."* (Male, Policy maker).

Opinions on potential of current interventions in leading the country towards malaria elimination

Two main viewpoints were expressed regarding the potential of current interventions in leading the country through elimination by 2030. One viewpoint, expressed by a majority of the participants, was that current interventions would not be sufficient to achieve elimination even if they were utilized fully and effectively. One reason given was that the current interventions do not address challenges such as insecticide resistance and changes in mosquito biting behaviours. As one community leader explained, *"I really do not think that the insecticide-sprays or the bed nets are enough, because if they were enough we would not have malaria anymore. I sleep under a bed net every night, but mosquitoes still bite me when I am outside cooking or chatting with my family and friends. Sometimes I also spray my house with insecticides, but when I go inside to sleep, I see there are mosquitoes still. So then I know that these sprays are useless."* (Female, Community member).

An opposite viewpoint was that the currently available interventions would be enough to lead the country through elimination if they were utilized to their maximum potential. As pointed out by one research scientist, *"We already have what it takes to achieve elimination. If bed nets were properly made, properly distributed and properly used, why would we not eliminate the disease? If they killed mosquitoes as they are supposed to, if the universal distribution was actually universal, and if people actually slept under bed nets, I do not think we would need anything else…"* (Female, Scientist).

Other participants pointed out that the current interventions are passive rather than active. That is, they only target mosquitoes coming to human dwellings rather than actively targeting them in their larval habitats and hiding places. As one policy maker stated, *"We need means to target and eliminate all the mosquitoes, not just the ones that get inside the house. If we decide to kill mosquitoes, then we should really kill all of them. We should target them at larval stage and adult stage to make sure that we are not leaving any windows for escape."* (Male, Policy maker).

Opinions on the need for alternative interventions for malaria elimination in Tanzania

There were diverse inputs from participants on the need for complementary interventions for malaria elimination in Tanzania, although majority participants agreed that it would be unavoidable to have some of the alternative approaches used to complement current ones. Insights that emerged most clearly included: a) the importance of learning from similar countries that have achieved elimination, b) importance of knowing more about current interventions, including where or why they have failed or succeeded, and c) the need to consider combinations of interventions as a more holistic approach to achieve malaria elimination.

Those participants who emphasized the value of learning from other successful countries argued that there was no need to develop interventions from scratch, and that the country should follow in the footsteps of those who had been successful in eliminating malaria. Other participant noted that, since malaria prevalence was not homogeneous across the country, it would be essential to employ different interventions in different settings based on the specific conditions. For example, one participant stated, *"Malaria prevalence is not the same in all the country. There are parts of the country that are near elimination, and there are parts that have prevalence in double digits. This should tell you that one single method is not enough for the whole country. You need to look at different places and figure out what can work where."* (Female, Regulator).

Participants who recommended combinations of interventions argued that we now have greater knowledge of mosquito behaviours than in the past, and that this knowledge can be used to target them from multiple angles to accelerate elimination. In one of the FGDs, one participant noted that *"In order to really eliminate mosquitoes we need a combination of different strategies…We need to target all the water bodies to get rid of the larval stages, then all the hiding places like long grass and bushes, and then in the houses where they go to look for people to bite. If we do all of this, can you tell me how we can still have malaria in our country?"* (Male, Policy maker).

There were also participants who suggested that it was not wise to rush to new interventions without learning from limitations of current interventions, and possibly addressing those first. In one session, there was an elaborate pronouncement by one policy maker, who noted that, *"Why aren't the bed nets killing mosquitoes? Why are the indoor insecticide sprays not killing mosquitoes? We have heard a lot about mosquitoes being resistant to the insecticides, but I still think we have not answered the question of where the resistance is coming from; what causes it and how it can be prevented or corrected. And also, do people know that the insecticides no longer kill mosquitoes? And if this is already a common knowledge, why are we still using these insecticides? I am sure that it costs a great deal of money to treat all the bed nets in the country with insecticides; but if these insecticides no longer work as insecticides, then why are we still using them?"* (Male, Policy maker).

Opinions on the potential of the selected alternative interventions for malaria elimination in Tanzania

Discussions on alternative interventions for malaria elimination were based on participants' opinions about their effectiveness, sustainability, safety, as well as about Tanzania's readiness to adapt the interventions. There was a wide variation in levels of preference for different intervention options as described below:

Improved housing: All stakeholder groups associated improved housing conditions with reduced malaria risk. However, there were disagreements on need for the government to support transition towards better living conditions in malaria endemic communities. While community members were strongly supportive of this idea, policy makers were hesitant, pointing out issues of sustainability, affordability and competing government priorities.

The community members, in support of improved housing, argued that no intervention would be fully effective without adequate housing. Specifically, they noted that none of the other interventions under discussion would be particularly useful, if people continued to live in poorly-constructed houses with gaps on walls, roofs, doors and eave spaces. They further stressed that the government could indeed afford housing for the poorest community members living in areas with high malaria burden. The community members proposed several ways that the government could assist these communities, such as by providing loans for people to build improved houses, subsidizing prices for building materials or building and renting houses to the poorest at a reduced price. As one community member said, *"If the government could listen, I would advise them to assist people, especially the poor people, to build improved houses. They can maybe build the houses, and people can repay the government slowly, everyone can pay according to what they can afford."* (Female, Community member).

Policy makers also agreed that improved houses provide extra protection against malaria-transmitting mosquitoes. However, they were against the idea of the government building or modifying houses for poor people living in areas of high malaria transmission. They noted that it is not the responsibility of the government to build houses for citizens, and that given the required magnitude, the program would be expensive and unsustainable. As one policy maker said: *"You know our country is still poor, which means that a lot more people live in poverty than not. If you say that we start building or improving houses for all the poor people, then we will not have money for any of the other important things like health care and education."* (Female, Policy maker). Additionally, policy makers also indicated that building better houses alone would not be enough to eliminate malaria; a lot more effort would still be needed to ensure that mosquitoes are controlled in their larval habitats and hiding places.

Research scientists and regulators also agreed that it would be advantageous if poor people in malaria endemic areas had access to better housing. Nonetheless, they too noted that it would not be sustainable for the government to support this initiative, or even to get funding to investigate its potential. As one researcher noted: *"For house improvement, no one denies that this works. The only problem is cost implications; that could be one of the reasons that this has not been taken up. Also, the way our research is organized and funded does not help in things like house improvement. It is difficult to get funding for this"* (Male, Scientist).

Larval source management: Two strategies were discussed regarding this intervention: environmental management and larviciding (Table 1). However, most of the interest was directed towards larviciding. One major issue voiced by all stakeholder groups was lack of clear regulations or enforcement on environmental management regulations, especially in relation to settlement planning and waste water management. Community members complained about lack of regulations on where people build, cultivate crops or manufacture bricks for construction, which often results in the accumulation of standing water near settlements, increasing the risk of malaria and other mosquito-borne diseases. In the words of a community member, "*The town is rapidly growing now. There were parts of the town that people were allowed to make bricks in the past; no one lived there at the time. But now many people live there, and it is not safe because there are so many brick-pits, hence so many mosquito breeding places…It would be important if there were requirements,* [for example] *that the brick makers move to other unoccupied places, or* [that] *they should be required to fill in the pits"* (Female, Community member).

The use of larvicides for malaria control was highly preferred across the stakeholder groups, but with some caveats. Policy makers strongly supported the use of bio-larvicides, stating that the government had invested on creation of a bio-larvicide plant as part of the national strategy towards malaria elimination, but that use of this bio-larvicide remained low. *"The biolarvicides we are producing are designed to only affect mosquitoes, so they are relatively safe on the environment. We expected a high uptake from community and civil organizations, but I am sad to say that we are getting more customers from outside the country than within the country…."* (Female, Policy maker). Research scientists were also supportive of larviciding for malaria elimination, but they noted that the efficacy of the locally produced bio-larvicides should be evaluated since any perception of low efficacy might cause low uptake.

While a majority of the community members were in favour of larviciding for malaria control, a few members expressed concerns that there were so many water pools in their villages, particularly in the rainy season, that it would be difficult to treat all of them with larvicides without harming the environment, particularly the fish. One person stated: *"I would also like to stress that I do not trust this idea of putting chemicals in water. We all know that all of this water makes its way into the river where we get our fish. If we treat all the pools then that means a lot of chemicals will be going to the river. Now, are you telling me that it will not harm the fish? Most of us are fishermen here and our fish is part of who we are. Anything that can harm the fish will not be welcomed here. Maybe if you want to put these chemicals, you can do it during the dry season, but then there are no many mosquitoes during this time, so it will just be a waste"* (Male, Community member).

MDA using the endectocide, ivermectin: MDA with ivermectin is currently undergoing trials as a potential vector control tool, but there are already several completed trials demonstrating impact on mosquito populations and malaria burden (14,56). When given to humans and/or cattle, it kills malaria vectors that bite these hosts. The drug was widely known among all stakeholder groups as it is already widely distributed for control of lymphatic filariasis in humans (41,42) and several cattle diseases (57).

Community members referred to it as *Usubi*, and spoke of 'health workers' going from house to house every year to distribute the drug and encourage people to take it for control of *Matende* (elephantiasis) and *Mabusha* (hydrocele), conditions commonly associated with lymphatic filariasis. Despite the high awareness of this drug, there were mixed views among the stakeholder groups on its use for malaria control. Regulators, policy-makers and research scientists were hopeful and supportive of the approach, given its safety and effectiveness for control and treatment of lymphatic filariasis in Tanzania. They argued that deploying it for control of malaria-carrying mosquitoes would represent an important advantage at relatively low cost. They also stressed the need to spend time and resources to educate and raise awareness of the alternative use of ivermectin among target communities.

Community members on the other hand had strong objections to this intervention, reporting negative experiences with previous mass drug administration (MDA) campaigns, particularly of Praziquantel, which is commonly used for treatment and control of schistosomiasis among school children. They reported that a number of children who received the drug suffered fainting spells in schools, and this resulted in negative sentiments among community members. They also noted that generally people did not like to take medicines. One participant stated: *"I really must tell you that these medicines that you have to swallow have a challenge. When they brought Usubi, even with all the education and the advocacy they had provided, people still did not take the medicines. Some people just picked it so as not to make the health workers feel bad, but after they* [health workers] *left people threw the medicine away."* (Male, Community member).

Targeted spraying of mosquito swarms: A great deal of scepticism was expressed by all stakeholder groups about sustainability and feasibility of targeted spraying of swarms of *Anopheles* mosquitoes. It was noted that the approach would require extensive community participation, and would be expensive. One participant stated: "*The setback with this is that you need a lot of people to do that, so it may also be expensive. But I agree maybe you use less insecticides, but if you are worrying about the cost of the insecticides, you will still be spending more in paying people to spray*" (Male, Policy maker). Community members also pointed out that it would be inconvenient to spray at the time of the day when mosquitoes swarm and in many of the locations where they do so: *"…it will be difficult to find someone at home during that time, people will still be at work, or they will be too tired to accept more work."* (Male, Community member).

Modified mosquitoes: This possibility of releasing modified mosquitoes generated a lot of discussions and resulted in polarized viewpoints among all stakeholder groups. Although groups were introduced to different technological approaches constituting mosquito modification (i.e., sterile insect technique, genetically modified-sterile mosquitoes and gene drive technology), most of the interest centered on implications of gene drive technologies, particularly those used for suppression of malaria vector populations.

Scientists were the most critical of gene drive technology. They questioned its safety and the country's readiness for such advancements. They also pointed out that there are still a lot of unknowns, and that

long-term research would be needed to provide evidence on various aspects of the technology. They expressed concerns about possibility of mutations in either the *Plasmodium* parasite or the modified mosquitoes themselves. Specific concerns in this case were that the modified malaria vectors could become vectors for other diseases or the *Plasmodium* parasite could mutate and survive in other mosquito species. The fact that the technology would target a single malaria vector was also seen as a risk as this could possibly increase the prevalence or vectorial capacity of the other malaria vectors. Targeting one mosquito species was also seen as a drawback in securing community acceptance. One participant stated: "*For the people, no malaria means no mosquitoes. They still cannot distinguish between malaria-transmitting and non-malaria transmitting mosquitoes, so if you tell them that you are controlling malaria then they need to see mosquitoes gone."* (Female, Scientist). The scientists were also concerned that there were not many African and particularly Tanzanian scientists taking leading roles in this research. One scientist stated: *"There are more fears than certainty regarding this technology. It is mainly being driven by foreigners. I worry that there are not many African researchers participating in the detailed research of this technology"* (Female, Scientist).

Policy makers were divided in their views regarding gene drives. Some were in favor of it, pointing out that it was environmentally friendly and required little compliance from communities, yet others were skeptical, noting that there is currently a great deal of controversy over genetically-modified food products, thus it might be unwise to introduce another genetically-modified organism. One policy maker said; "*We are already struggling with acceptance of GM crops, adding yet something like this may bring havoc in the country. Let them [*other countries*] try it first, let us learn from our neighbours and go last in this."* (Female, Policy maker). The policy makers also recognized that the technology is not yet ready, and cannot be considered in the 2030 malaria elimination campaigns.

In contrast, and significantly, community members expressed a great deal of fascination with the technology. They were struck in particular by the fact that it will require little work or participation from residents, compared to traditional malaria interventions. They also expressed a preference for this technology since it was seen to pose the least harm to the environment, particularly to fish. One participant said: "*I like that it does not have any chemicals, so the environment and the fish are all safe, but the malaria-mosquitoes will be gone* (Male, Community member).

Regulators pointed out that, while the potential of gene drive technologies ought to be explored, there are currently no policies and regulations for their governance, and in order to put those in place, more research is needed to assure short- and long-term safety. One participant said: *"There are regulations for GMOs, but this technology you have is not GMO, rather GM edited organisms. Gene-edited is not the same as GMO. We do not have policies or regulations for that. I believe you can advise us on this; provide all the information needed and the evidence of its safety and we can add this into the regulations concerning GM organisms"* (Female, Regulator).

Spatial repellents: All stakeholder groups agreed that this technology would be appropriate as complementary (rather than primary) intervention for malaria control and elimination. Scientists however

indicated that there was still insufficient evidence to indicate the best spatial repellents, and their availability, cost and feasibility of use.

Community members spoke positively about this technology, saying that it was most useful when people were outdoors in early night hours, when cooking, eating and relaxing with their family and friends before going indoors to sleep. They alleged that it would be best if the government could distribute bed nets together with spatial repellents as a package in order to tackle the problem of mosquitoes changing their behaviours. One participant stated: *"We have been told that mosquitoes are clever and have changed their biting times, so we have to be smart too and respond to that change using these repellents. If the government can provide these repellents to every household and teach them when, where and how to use them, I think we can make a very big progress in ending the malaria problem."* (Female, Community member).

Discussion

This study explored opinions of key stakeholders on Tanzania's progress towards malaria elimination, and their views on suitability and potential of six alternative interventions that might complement efforts to achieve that goal in the future. The stakeholders weighed alternative approaches to malaria control and elimination, rather than focusing the discussions on individual approaches.

Our findings reveal a considerable agreement across the stakeholder groups on the extent of progress achieved in the control of malaria in Tanzania over the last decade. It was also noted that policy makers, regulators and scientists pointed to statistical evidence of declining malaria prevalence, as reported in recent Tanzania's malaria indicator surveys (TMIS) (58,59). On the other hand, community members mostly pointed to their lived experiences of witnessing fewer episodes of malaria, and reduced severity of the disease. All participants commended the country's efforts in providing universal coverage with LLINs, reliable diagnosis and affordable treatment, all of which are also already demonstrated by various studies (6,7,60). There was also a general agreement that current interventions are not sufficient to achieve further reductions in malaria burden. Participants listed various challenges, such as insecticide resistance and outdoor biting exposure, which are also widely demonstrated in field studies (4,6).

While there was consensus that new, complementary interventions or technologies were needed to push the country further towards elimination, opinions differed on what technologies deserved prioritization and investment. The most preferred of the alternative interventions were larviciding and spatial repellents. During the discussions, the participants proposed that low-cost technologies e.g. spatial mosquito repellents could be used to provide temporary relief against early-evening and outdoor-biting mosquitoes, thereby complementing LLINs. Support for larviciding could be found in all stakeholders as well, and it was the most preferred option among policy makers, regulators and scientists. While community members had concerns regarding the environmental impact of larviciding, particularly on fish stocks, they did not have strong objections towards it. They rather offered their advice that it is done during the dry

season when there is a lesser likelihood for the larvicides to get to the water. Current national policy already includes larviciding as a way to achieve further reductions in malaria incidence (2).

Insecticide-spraying of mosquito swarms was the least preferred by all stakeholder groups, due to perceived environmental harm, high cost and the assumed difficulty of area-wide implementation. This viewpoint was however not reflected in a survey previously done in the same settings as the community members, which showed that interventions targeting swarming mosquitoes were widely accepted in the community as swarming mosquitoes were considered dangerous (61). This difference in opinions is likely due to the fact that the community members involved in the FGDs had no real experience with the intervention compared to the community members assessed in the survey; hence they were unlikely to accept it.

One surprising outcome was the degree of skepticism that scientists expressed about prospects of mosquito modification technologies, particularly those based on gene drive constructs – and the comparatively more positive views expressed by, among others, community members. This is an important observation since any introduction of gene drive-based methods for malaria control in Tanzania will require strong support by local scientists, both because of operational reasons and because of the influence that scientists have on perceptions of all the other stakeholder groups (62). Some of the concerns discussed by researchers, such as their doubts about safety or undesirable mutations, can be addressed by producing more scientific evidence, but others, and in particular their complaint about inadequate involvement of African scientists in the development of the technology, require changes in the social and political organization of gene drive research approaches. Similar concerns have been observed in a recent study that explored perceptions of scientists in Nigeria on the potential release of genetically modified mosquitoes (63). In this study, policy makers and regulators repeatedly claimed that they needed further information from scientists to make informed decisions. This emphasizes the persuasive power of scientists, and stresses the need to not only expand involvement of local scientists on development of the technology, but also the need to encourage and strengthen collaboration between scientists, policy makers and regulators when developing or evaluating alternative technologies.

Community members, in contrast, expressed strong support for gene drive technology. They perceived it as being environmentally safer, and noted that it would require little work by communities. This was an unexpected finding, and contrasts with studies conducted elsewhere. A recent study from Mali, for instance, reveals that community members were reluctant to accept the release of genetically modified mosquitoes in their villages, arguing that they would prefer for this technology to be tried elsewhere first to show evidence of safety (64). A recent US study however demonstrated that nearly two thirds of people trusted universities and the department of agriculture (but not the private sector nor the department of defense) to research gene drives (65). This further stresses on the need to earn approval of scientists, and to strengthen communication between scientists and communities in order to avoid delays in getting community acceptance of this technology.

Preference for house-improvement was highest among community members, who emphasized that it was a more sustainable approach to malaria prevention, and would have a similarly positive impact on control of many other vector-borne diseases. This point of view is supported by historical evidence that links successes against malaria with improved housing conditions in Europe and North America (66), and also recent findings of reduced malaria transmission following better housing or house screening (22,33). In contrast, scientists and policy makers were skeptical about investment on housing improvement as a malaria control technology, mostly because of the perceived high cost and lack of political feasibility.

MDA with ivermectin also generated polarized views among the stakeholder groups. Strong preference for the technology was observed among policy makers, regulators and scientists. It was on the other hand least preferred by the community members, who reported negative experiences with MDAs campaigns in primary schools for control of schistosomiasis. These reports echo studies conducted in Tanzania and Cameroon showing that adherence to ivermectin MDA was associated with previous experiences and perceptions towards MDAs, even when they concerned other drugs (67,68). Community members also pointed out that people generally did not like taking drugs, particularly when they did not suffer symptoms, an observation which could potentially limit scale-up of the approach.

This study had a number of limitations. Since a number of the approaches discussed in this study were new or not very well known among the participants, they were introduced and briefly described by the facilitator, which necessarily influences participants' perceptions. To minimize this effect, participants were first asked to list and discuss the approaches they were familiar with, and only after they had exhausted what they knew were they presented with additional approaches in generic format. Equal amount of time and information was given for each technology. Additionally, participants were very engaged with the discussion and asked a lot of questions before giving their opinion. To minimize the influence that the information provided by the facilitator might have had on participants' views, only generic responses were given, and the questions were often reverted back to the participants themselves to elucidate the reasons for their queries.

Conclusion

While it seems inevitable that new tools will be needed for Tanzania to achieve malaria elimination by 2030, it remains to be seen which particular combination of technologies will be adopted in the near future. Different stakeholders perceive differently the advantages and disadvantages of each individual approach to malaria control and elimination, and assess individual options in the context of existing methods and other potential alternatives. All stakeholder groups, however, claimed that they depend on the advice provided by scientists to make informed decisions. This shows the critical role scientists play as gate-keepers for new interventions, and suggests the importance of a robust dialogue and clear communication between scientists, policy makers, regulators and community members. The enthusiasm of community members to contribute to the knowledge and innovation towards malaria elimination stresses the need to actively involve citizens in the design, development and implementation of strategies to eliminate malaria in Tanzania. While scientists, regulators and policy-makers describe progress against

malaria in terms of declining parasite prevalence, community members describe progress in terms of their daily life experiences. It is therefore vital to encourage and strengthen dialogue between scientists, policy makers, regulators and communities regarding any new interventions being considered or developed for malaria control and elimination. Lastly, the need for local scientists to engage in development and evaluation of new technologies such as gene drives is desirable to promote uptake, should such technologies prove effective.

Declarations

Ethics approval and consent to participate

This study is nested as a public engagement component under two larger studies at Ifakara Health Institute titled "*Anopheles funestus gene flow studies and rearing methods*" and *"Demonstrating complete disruption of residual malaria transmission by eliminating Anopheles funestus mosquitoes from Tanzanian villages".* Ethical approvals for this project were obtained from Ifakara Health Institute's Institutional Review Board (Protocol ID: IHI/IRB/EXT/No: 007 - 2018) and the Medical Research Coordinating Committee (MRCC) at the National Institute for Medical Research, in Tanzania (Protocol ID: NIMR/HQ/R.8a/Vol.IX/2895), as well as University of the Witwatersrand (UW) in South Africa (Clearance certificate No. M180820). Meetings were held with leaders of each stakeholder groups to request their consent to conduct this study and to recommend participants from their institutes. Upon consent, formal letters were sent to each of the recommended participants to invite them to the discussions. Written consents were also sought from all participants of this study, after they had understood the purpose and procedure of the discussions.

Consent for publication

Permission to publish this study was obtained from NIMR (Ref: NIMR/HQ/P.12 VOL XXIX/37).

Availability of data and material

All data for this study will be available upon request.

Competing interests

The authors declare no competing interests.

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Authors' contributions

MFF was involved in study design, data collection, entry and analysis, interpretation of the results and drafting of the manuscript. FOO, NC and AJL were involved in study design supervision and critical revision of the manuscript. AK, BT, PC, NK, PK and BE were also involved in study design, data collection and critical revision of the manuscript. All authors read and approved the final manuscript.

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