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Routine malaria vaccination in Africa: a step toward malaria eradication?

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Abstract

Malaria remains a significant global health challenge, with nearly half of the world's population at risk of infection. In 2022 alone, malaria claimed approximately 608,000 lives, with 76% of these fatalities occurring in children under the age of five, underscoring the disease's disproportionate impact on vulnerable populations. Africa bears the highest burden, accounting for 94% of global malaria cases. For over 60 years, the development of a malaria vaccine has been a critical objective for scientists and governments, with substantial efforts directed toward this goal. Recent progress has led to the approval of the first malaria vaccines, RTS,S/AS01 (Mosquirix®) and the R21/Matrix-M vaccine. Inspired by the promise of these vaccines, the global malaria community has renewed its focus on malaria eradication, 50 years after flawed earlier eradication efforts in the mid-twentieth century. Since the World Health Organization's endorsement of RTS,S in 2021 and R21 in 2023, several African countries, beginning with Cameroon, have integrated these vaccines into routine immunization programmes. This review examines the role of routine malaria vaccination in Africa as a key strategy toward malaria elimination, explores challenges and solutions for widespread vaccine implementation, and discusses future directions in the ongoing fight to eliminate malaria on the continent.

Keywords Malaria, Vaccine, Elimination, Africa

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Background

Malaria is a major global health concern, with nearly half of the world's population at risk of infection [1]. This protozoan disease is caused by *Plasmodium* parasites and transmitted through the bite of female *Anopheles* mosquitoes. A number of species of *Plasmodium* can infect humans, with *Plasmodium falciparum* responsible for over 99% of malaria-related deaths [2]. Malaria is sensitive to climate factors, including temperature, rainfall, and humidity, which influence mosquito breeding and parasite development. Growing evidence suggests that climate change could shift malaria's geographical range, expanding transmission into areas where it has been previously controlled or emerging in regions that were not endemic. These changes pose new challenges for public health, particularly in regions vulnerable to rising temperatures and altered precipitation patterns [3].

According to the 2023 World Health Organization (WHO) Malaria Report [4], an estimated 249 million malaria cases occurred in 85 endemic countries in 2022, with a case incidence of 58 per 1,000 people at risk. In the same year, global malaria-related deaths were estimated at 608,000, with a mortality rate of 14.3 deaths per 100,000 people at risk. Alarmingly, 76% of these deaths occurred in children under the age of five, highlighting the disproportionate impact of malaria on vulnerable populations. Over 50% of total deaths occurred in just four countries: Nigeria (31%), the Democratic Republic of the Congo (12%), Niger (6%), and Tanzania (4%). Furthermore, approximately 70% of the global malaria burden is concentrated in 11 countries, including Burkina Faso, Cameroon, the Democratic Republic of the Congo, Ghana, India, Mali, Mozambique, Niger, Nigeria, Uganda, and Tanzania [5]. These figures highlight the severe malaria burden in African countries, where the disease remains a significant public health challenge, contributing to high morbidity and mortality rates despite global control efforts (Fig. 1).

In May 2015, the World Health Assembly adopted the Global Technical Strategy for Malaria 2016–2030, providing a framework for countries working to control and eliminate malaria. The 2030 goals include reducing malaria case incidence and mortality rates by at least 90% compared to 2015 levels, eliminating malaria in 35 more endemic countries, and preventing its resurgence in malaria-free countries [6]. However, progress is significantly off track, and if current trajectory persists, the target for reducing case incidence and mortality by 2030 will be missed by 89% and 88%, respectively. Meanwhile, African countries, bearing the highest burden, have made progress through rapid diagnosis, mosquito net distribution, insecticide use, and preventive treatments for high-risk groups. From 2000 to 2022, malaria incidence in the WHO African Region declined by 40%, and mortality decreased by 60%. However, challenges such as climate change, poverty, inadequate health services, outdoor transmission, and resistance to drugs and insecticides continue to hinder efforts [7].

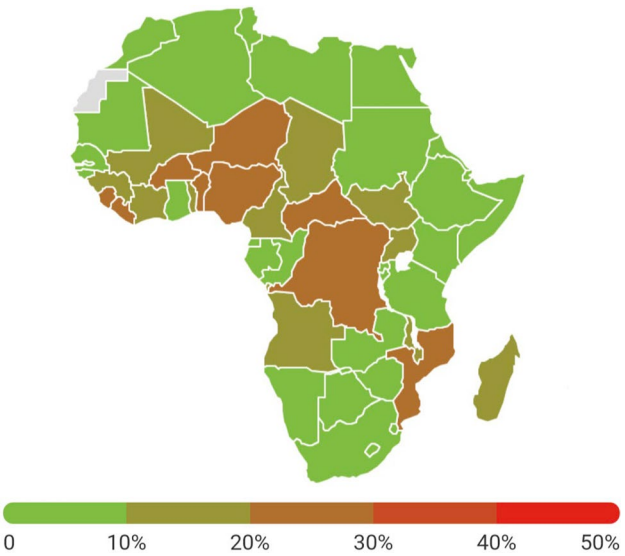

Fig. 1 Percentage of deaths caused by malaria in children under 5 years of age in Africa (2000, 2021); source: UNICEF, 2024

Malaria eradication will only be achieved when all human-infecting *Plasmodium* parasites are eradicated globally [8]. While current control measures such as insecticide-treated bed nets (ITNs), indoor residual spraying (IRS), and intermittent preventive treatment (IPT) for high-risk groups—particularly pregnant women and young children—have contributed to significant reductions in malaria cases, these strategies alone have proven insufficient for complete eradication. The development and deployment of malaria vaccines represent a critical advancement in the fight against malaria, offering a new tool that could significantly enhance control efforts. Routine malaria vaccination, especially in regions like Africa, where the disease burden remains highest, could prove pivotal in breaking the transmission cycle and reducing malaria incidence and mortality. This review aims to explore the role of routine malaria vaccination in the broader strategy to eliminate the disease, focusing on their potential to complement existing control measures and accelerate progress toward malaria elimination in Africa.

The journey of malaria vaccines research and development

The development of malaria vaccines has been a 60-year endeavour, beginning in the early 1960s, inspired by the success of vaccines for diseases like polio, measles,

diphtheria, tetanus, and rabies [9]. The eradication of smallpox demonstrated the power of vaccination in combating infectious diseases globally. However, early efforts to create a malaria vaccine were met with significant challenges. Researchers soon realized the difficulty of developing such a vaccine due to the malaria parasite's complex biology and life cycle, as well as its ability to evade the human immune system. The parasite's (*P. falciparum*) intricate genome and lack of sterile immunity further complicated vaccine development, making malaria vaccination a multifaceted challenge [9].

The first promising studies for a malaria vaccine emerged in 1967, when mice were immunized using live, radiation-attenuated sporozoites. This approach offered significant protection, as the immunized mice were later able to resist infection after being injected with normal, viable sporozoites [10]. These early results demonstrated the potential for a vaccine against malaria. Since the 1970s, substantial progress has been made in malaria vaccine research and development, focusing on approaches that aim to replicate the protective effects seen in animal models. These advancements have paved the way for ongoing research efforts to develop an effective malaria vaccine for widespread use in humans [11].

The RTS,S vaccine is one of the earliest malaria vaccine candidates that eventually achieved success [12]. In the 1980s, scientists at the Walter Reed Army Institute of Research (WRAIR) in the U.S. collaborated with researchers from SmithKline and French to develop a protein subunit vaccine targeting the sporozoite stage of the malaria parasite. Their approach aimed to stimulate the immune system by using the circumsporozoite protein (CSP), a surface protein of the sporozoite. Although previous attempts to target CSP had failed, GSK scientist Joe Cohen proposed a new strategy. He used a hepatitis B virus surface protein (HBsAg) as a scaffold to present CSP, creating a virus-like particle to enhance the immune response. Despite this innovation, the immune response remained insufficient, leading the team to experiment with different adjuvants to boost the vaccine's efficacy [13].

A major breakthrough came with the development of a human challenge model by WRAIR, enabling the team to safely infect human volunteers with *P. falciparum* and test various vaccine candidates. This involved infecting *Anopheles* mosquitoes with malaria parasites and allowing vaccinated volunteers to be bitten, monitoring them for infection. Volunteers who became infected were promptly treated with anti-malarial drugs. In 1997, the researchers found an adjuvant formulation that, when combined with the CSP-HBsAg construct, provided strong protection against malaria [13]. Large-scale human trials followed, initially in adults, then in adolescents, children, and infants in malaria-endemic regions of sub-Saharan Africa. In 2004, a double-blind randomized controlled trial conducted in Mozambique provided initial evidence that RTS,S was safe and effective among young children.

In November 2012, a phase III trial of the RTS,S malaria vaccine demonstrated modest protection against both clinical and severe malaria in infants [14]. In 2015, the European Medicines Agency (EMA) granted a positive opinion for the use of Mosquirix® in children aged 6 weeks to 17 months. Pilot programmes were initiated in Malawi, Ghana, and Kenya by 2019 to evaluate the vaccine's real-world impact [15]. By October 2021, the World Health Organization (WHO) officially endorsed Mosquirix® for broad use in children, making it the first malaria vaccine approved for widespread use and the first vaccine to target a human parasitic disease [15].

Building on the development of the RTS,S vaccine, the R21/Matrix-M malaria vaccine was created by the University of Oxford and its partners to improve efficacy and accessibility [16]. Like RTS,S, R21 targets the circumsporozoite protein (CSP) found on the surface of *P. falciparum* sporozoites, but with important enhancements. R21 features a higher proportion of CSP and employs a redesigned fusion with Hepatitis B surface antigen (HBsAg), increasing particle formation by reducing unfused HBsAg. This modification enhances the density of CSP on the virus-like particle, improving the vaccine's immunogenicity. These advancements allowed R21 to achieve higher efficacy, and in December 2023, it was prequalified by the World Health Organization, making it the second malaria vaccine to receive global approval for use [17].

Both R21 and RTS,S malaria vaccines demonstrate robust community-level effectiveness; however, R21 offers a notable advantage in production efficiency than RTS,S [18]. This higher yield is attributed to R21's innovative design, which features a higher density of circumsporozoite protein (CSP) on its virus-like particles. This approach avoids the dependency on excess hepatitis B surface antigen (HBsAg) required by RTS,S, streamlining the production process [19]. The substantial increase in production capacity of R21 is critical for addressing access challenges in endemic regions, particularly in low-resource settings. Its cost-effective and scalable production enhances its potential for widespread use, making it as a practical and impactful tool for malaria elimination programmes [20, 21].

Routine malaria vaccination in Africa

In 2023, the World Health Organization (WHO) recommended the systematic use of the RTS,S/AS01 and R21/Matrix-M malaria vaccines to prevent *P. falciparum*

malaria in children from malaria-endemic regions, focusing on areas with moderate to high transmission rates [22]. Following a WHO recommendation, several African countries incorporated malaria vaccination into their national immunization programmes. Cameroon became the first country to implement routine malaria vaccination on January 22, 2024 [23]. By February 9, 2024, approximately 10,000 children in Cameroon and Burkina Faso had already received the RTS,S vaccine, marking a significant step forward in expanding malaria prevention efforts across the continent [24].

In 2024, over 20 African countries are set to incorporate malaria vaccines into their routine immunization programs, with nations such as Cameroon, Burkina Faso, Benin, Liberia, and Sierra Leone at the forefront of this initiative [25]. The expansion of malaria vaccination across Africa is expected to significantly improve access to malaria prevention, potentially saving tens of thousands of young lives annually. To support this effort, the WHO Regional Office for Africa launched the Accelerating Malaria Vaccine Introduction and Rollout in Africa (AMVIRA) in January 2024 [25]. AMVIRA seeks to enhance technical assistance to Member States, facilitating the effective introduction and deployment of malaria vaccines. Additionally, the initiative aims to bolster coordination among partners at national, regional, and global levels, ensuring an efficient and streamlined vaccination rollout.

Malaria vaccination in Africa has demonstrated significant impact. The WHO reports that since the launch of the Malaria Vaccine Implementation Programme (MVIP) in Ghana, Kenya, and Malawi in 2019, there has been a 13% reduction in mortality among vaccine-eligible children and a marked decrease in severe malaria-related hospitalizations over 4 years [26]. The success of the MVIP and insights gained from the pilot programme played a crucial role in guiding the development of the R21 malaria vaccine. These lessons also contributed to the efficient progress in developing additional malaria vaccines, ultimately leading to WHO's recommendation for the R21 vaccine as the second approved malaria vaccine. This achievement reflects the growing potential of vaccination programmes in curbing malaria's burden across endemic regions [27].

Vaccination is a cornerstone of global health, credited with eradicating smallpox and significantly reducing the burden of numerous diseases [28, 29]. Smallpox, once claiming over 300 million lives with a mortality rate of 30%, was eradicated in 1977 through a WHO-led vaccination efforts [26]. Immunization efforts have since saved 154 million lives over 50 years, reducing global infant mortality by 40% and contributing 10.2 billion healthy years to populations worldwide. Vaccination efforts have also enabled over 20 million individuals, who would have otherwise been paralyzed by polio, to walk, with global eradication of the disease now within reach [30]. The COVID-19 pandemic further underscored vaccination's value, spurring the largest immunization campaign in history [31, 32]. Despite challenges such as inequitable distribution and pandemic-related disruptions, vaccination remains pivotal in disease control and safeguarding health.

These testimonies from already controlled infectious diseases demonstrate that malaria eradication or significant reduction is achievable through vaccination and coordinated efforts. The introduction of routine malaria vaccination, particularly in endemic regions, represents a critical advancement in this challenging endeavor [33]. Fifty years after a flawed attempt to eradicate malaria in the mid-twentieth century, the global malaria community is once again focusing on eradication [34, 35]. This momentum has been steadily building, with more than half of the world's countries now malaria-free. Since 2000, global progress has accelerated, driven by new technologies and substantial increases in political and financial commitment from countries, regions, and global partners. Annual spending on malaria increased from approximately $1.5 billion in 2000 to $4.3 billion in 2016, resulting in a 36% decline in malaria incidence and a 60% reduction in mortality. Prompted by these achievements, the Lancet Commission on Malaria Eradication now views global malaria eradication by 2050 as a bold, yet achievable and necessary goal [35]. In contrast, the WHO has been cautious about committing to a specific timeline. Despite advocating for malaria eradication since 1948, the WHO emphasizes that the current burden of cases remains high and that optimal tools for eradication have not yet been developed. The WHO projections indicate that, using existing tools, Africa may still face 11 million malaria cases by 2050 [36]. In this context, malaria vaccination emerges as a potentially transformative intervention. When effectively implemented, vaccines can significantly reduce transmission rates, complementing other preventive and treatment measures. As such, malaria vaccination represents one of the strongest tools available to control and eventually eliminate the disease, bridging critical gaps in the current arsenal and accelerating progress toward global malaria eradication [37].

Malaria vaccination not only offers significant health benefits but also demonstrates cost-effectiveness. According to the WHO's Choosing Interventions that are Cost-Effective (WHO-CHOICE), an intervention is considered cost-effective if the cost per Disability-Adjusted Life Year (DALY) averted is less than three times the country's annual Gross Domestic Product (GDP) per capita [38]. For sub-Saharan Africa, with an average GDP

per capita of US$1,636.8, according to the World Bank Group [39], a malaria vaccine would be cost-effective if its cost per DALY averted was under US$4,910.4. A study by Schmit et al. [40] evaluating the R21/Matrix-M malaria vaccine showed that its incremental cost per DALY averted ranged from US$30 to US$139, under an assumed vaccine dose price of US$3, indicating that it meets the WHO-CHOICE cost-effectiveness threshold.

Further analysis reinforces the cost-effectiveness of malaria vaccines, even with a higher vaccine cost. A model by Kelly et al. [41] estimated that with a vaccine cost of US$10 per dose, the RTS,S vaccine could avert between 20,000 and 28,000 clinical cases, as well as 100 to 200 malaria deaths per 100,000 children vaccinated in low transmission settings over 15 years. The median cost per DALY averted was estimated to range from US$480 to US$682. In moderate to high transmission settings, the cost per DALY averted dropped to between US$175 and US$187 [41]. These findings confirm that, even at higher costs, malaria vaccines remain cost-effective, making them a valuable intervention in malaria control efforts. Similarly, according to Elabd and Duncombe [42], the R21 vaccine was almost as cost-effective as bed nets, the most efficient malaria intervention, with a cost of US$39/DALY for R21 versus US$38/DALY for bed nets. The RTS,S vaccine, although more expensive at US$129/DALY, still proved more affordable than mosquito control, the least cost-effective strategy, priced at US$296/DALY [42].

Furthermore, the Action and Investment to Defeat Malaria (AIM) 2016–2030 emphasizes the high cost-effectiveness of malaria control and elimination, with malaria prevention and treatment ranked among the most cost-effective public health interventions [43]. Investments in malaria control are not only health-enhancing but also yield significant economic returns. Between 2011 and 2014, malaria control cost only US$5–8 per case averted, generating millions in savings. Countries with malaria see 0.25–1.3% points slower GDP growth per capita than malaria-free nations, with malaria-affected countries experiencing five times slower GDP growth over 25 years [44]. An expenditure impact study found that for every US$1 invested in malaria control in Africa, there is an increase of US$6.75 in per capita GDP, further demonstrating the economic value of investing in malaria vaccination and elimination efforts [43, 45].

The financial support for malaria vaccination in sub-Saharan Africa has been crucial in increasing the feasibility of large-scale vaccination efforts. GAVI, the Vaccine Alliance, has committed US$155.7 million to support the RTS,S vaccine rollout in Ghana, Kenya, and Malawi through pilot programs [46]. Additionally, 12 countries across Africa are to receive 18 million doses of the RTS,S vaccine from 2023 to 2025, enabling further vaccine distribution [47]. Despite these efforts, the Global Technical Strategy for Malaria 2016–2030 estimates that funding requirements will increase from US$6.8 billion in 2020 to US$10.3 billion by 2030. A review of the World Malaria Report 2022 revealed that only 50% of the required funding was mobilized globally, indicating a significant funding gap that could hinder the scaling-up of malaria vaccination efforts [48]. Therefore, while malaria vaccination has proven cost-effective, continued investment is needed to meet the growing demand for these interventions.

Challenges and solutions to routine malaria vaccination in Africa

Despite the critical role routine malaria vaccination could play in combating malaria in Africa, several significant challenges must be addressed. The primary issue lies in the efficacy of available vaccines, which do not provide complete protection against malaria. Additional challenges include vaccine shipment and storage difficulties, as well as infrastructure and logistical constraints. Inadequate funding and resource allocation for malaria vaccination programs further hinder progress. Vaccine hesitancy, fueled by misinformation and skepticism, presents another major obstacle, alongside educational barriers and limited community engagement. Furthermore, a lack of understanding regarding the malaria vaccine among healthcare workers exacerbates the problem.

The genetic diversity of *Plasmodium* parasites poses a significant challenge to malaria control. Rapid mutation allows the parasite to produce variants that evade immune detection, reducing vaccine effectiveness, especially in regions with diverse strains [49]. This genetic variability limits the long-term efficacy of existing vaccines and complicates their application in different geographical areas. For example, the RTS,S malaria vaccine offers only 30–50% protection, which is insufficient to interrupt transmission, and its efficacy diminishes over time, necessitating multiple booster doses to sustain immunity [50]. This underscores the need for continued research to develop vaccines that provide broader, more durable protection against various *P. falciparum* strains. Achieving such advancements could significantly enhance global efforts toward malaria eradication, especially in regions with high parasite diversity.

Logistical barriers present significant challenges to the widespread distribution of malaria vaccines, especially in rural, malaria-endemic regions [51]. Many areas, particularly in sub-Saharan Africa, have underdeveloped healthcare infrastructure, making vaccines distribution difficult. Poor road networks hinder access to remote areas, and

healthcare facilities often lack the cold chain storage necessary to maintain vaccine efficacy. In addition, healthcare systems are frequently overwhelmed, and ensuring follow-up with patients may be inconsistent [52]. These logistical obstacles must be addressed to ensure effective vaccine delivery and maximize the potential of malaria vaccines to contribute to disease elimination, particularly in regions where the disease burden is greatest and healthcare resources are limited.

A further complication lies in integrating malaria vaccines into existing immunization programmes. Vaccines like RTS,S require four doses, making coordination with existing childhood immunization schedules complex. Ensuring that children receive all necessary doses on time is critical to the vaccine's effectiveness, yet tracking vaccination schedules in regions with weak health infrastructure remains difficult [53]. Many sub-Saharan African countries already face competing healthcare priorities, including managing immunization programmes for other diseases such as measles, polio, and diphtheria. The strain on resources means that policymakers must carefully balance the allocation of funding and personnel to ensure that malaria vaccines are integrated without undermining other essential health services [54, 55].

Vaccine hesitancy is another significant challenge in implementing routine malaria vaccination. In many African communities, misinformation, cultural beliefs, and mistrust of healthcare systems drive skepticism toward vaccines [56, 57]. This mistrust is often exacerbated by historical experiences with Western-led medical interventions, which have sometimes sparked suspicion and resistance [58]. Some individuals may fear potential side effects or doubt the vaccine's effectiveness, while others may oppose vaccination due to religious or cultural reasons [59]. Addressing these concerns requires comprehensive public health campaigns that engage communities, provide accurate information, and build trust in health systems. Healthcare workers, who are instrumental in delivering vaccines, must also be adequately trained and informed to address public concerns effectively.

The limited global supply of malaria vaccines presents other significant challenge to achieving widespread coverage in malaria-endemic regions [60]. Current vaccine production, including the RTS,S vaccine, falls short of meeting the demand, and manufacturing constraints, along with high production costs, further restrict the availability of vaccines for large-scale distribution [61]. These limitations hinder efforts to protect vulnerable populations, particularly in areas where the disease burden is highest. Ensuring a stable supply of vaccines is essential for successful malaria control and eventual eradication. To achieve this, sustained financial support from governments, global health organizations, and private-sector donors is critical. Long-term funding will enable increased production capacity and improve distribution infrastructure, ensuring that vaccines reach those most in need and contribute to reducing the global malaria burden.

Overcoming the barriers to effective malaria vaccination in Africa requires a coordinated, multi-level approach. Scientifically, continued innovation in vaccine development is critical to improving both efficacy and coverage. Logistically, strengthening healthcare infrastructure and supply chains is essential to ensure that vaccines reach the most vulnerable populations, particularly in remote and underserved areas. Financially, securing sustainable funding is crucial for supporting global vaccine production and distribution, enabling widespread coverage in regions with the highest malaria burden. On a social level, engaging and educating communities will play a vital role in reducing vaccine hesitancy and increasing public acceptance, which is key for successful immunization campaigns. Through comprehensive efforts addressing scientific, logistical, financial, and social dimensions, malaria vaccination can become a cornerstone in the global strategy to reduce malaria morbidity and mortality, particularly in Africa, where the disease's impact is most severe.

Prospects on further efforts and future directions for malaria elimination in Africa

Malaria elimination in Africa requires a multifaceted and coordinated approach beyond vaccination alone. Traditional preventive measures, including insecticide-treated bed nets, indoor residual spraying, eliminating mosquito breeding sites, public health education, and improving early diagnosis and treatment access, remain critical. Emerging technologies, innovations, and interventions are pivotal in supplementing these efforts.

Artificial intelligence (AI) and advanced technologies hold great potential in the fight to eradicate malaria [62]. Geographic Information Systems (GIS) can facilitate in real-time surveillance, mapping high-risk areas, and monitoring outbreaks. Mobile innovations, including smart apps, SMS, and USSD systems, is believed to enhance communication and enable early detection and treatment [63]. Drone technology has also been proposed and used in mosquito control through aerial insecticide spraying, identification of breeding sites, and deploying genetically modified mosquitoes to disrupt transmission. In addition, devices such as SolarMal and ThermaCell repellents have also been used to reduce mosquito populations [63].

Ongoing research is exploring how genetically modified mosquitoes, particularly those using gene-drive technology, could eradicate malaria, though this

approach has long been controversial. Gene-drive systems, such as CRISPR-Cas9, offer a promising strategy by promoting the preferential inheritance of genes that inhibit malaria transmission [64]. These genetic modifications either disrupt essential mosquito genes or introduce effector genes that confer resistance to the *Plasmodium* parasite, thereby reducing the mosquitoes' ability to spread the disease [65]. Studies suggest that gene drive-modified mosquitoes could significantly lower malaria incidence, with trials underway in countries like Burkina Faso and Kenya to assess their effectiveness across different transmission settings [66]. Meanwhile, challenges that need to be addressed include resistance emergence, ecological impacts, and ethical concerns regarding releasing genetically modified organisms [64].

Attractive toxic sugar baits (ATSBs) and biological larvicides are gaining attention as innovative strategies to disrupt mosquito breeding cycles while minimizing environmental impacts. ATSBs combine sugar-based baits with toxicants to attract and kill mosquitoes, proving effective across different ecological contexts. Trials in Zambia demonstrated ATSBs' ability to target *Anopheles* species, the primary malaria vectors [67]. Similarly, ATSBs containing boric acid significantly reduced *Aedes albopictus* populations in Taiwan, showing promise for integrated vector management [68]. Further studies on toxicants like tolfenpyrad and erythritol in sugar baits revealed high mortality rates in *Aedes aegypti*, suggesting that these formulations could strengthen mosquito control efforts [69, 70]. Despite their potential, challenges such as maintaining bait stability and attractiveness in varying environmental conditions remain, which could impact their overall efficacy [71]. Nonetheless, ATSBs align with sustainable pest management and offer a viable alternative to traditional insecticides.

In addition to efforts aimed at reducing mosquito populations, monoclonal antibodies (mAbs) are emerging as a promising intervention to prevent malaria by neutralizing the *Plasmodium* parasite before it infects red blood cells [72]. Recent studies have underscored the potential of mAbs, particularly L9LS, which has demonstrated significant efficacy in clinical trials [73]. L9LS specifically targets the sporozoite stage of *P. falciparum*, blocking the parasite's attachment to liver cells and promoting its destruction. By binding to a key protein on the sporozoite, L9LS interrupts the malaria life cycle [74]. In a phase 2 trial, L9LS showed 66–77% efficacy in preventing *P. falciparum* infection in children [73]. Additionally, optimized antibodies like MAM01 are being developed to enhance protection in pediatric populations, and could be the potential tool to reduce under five mortality due malaria in Africa as well other continents [75].

It is important to remember that the introduction of routine malaria immunization could significantly influence existing and emerging malaria prevention strategies, requiring a coordinated approach for optimal impact. Malaria vaccines may complement traditional measures like insecticide-treated nets, indoor residual spraying and tools like mobile health platforms to enhance prevention, diagnosis, and treatment coverage. However, vaccination could alter transmission dynamics, potentially affecting the efficacy of experimental strategies, such as genetically modified mosquitoes or attractive toxic sugar baits, which depend on high mosquito-human interaction. This underscores the need for careful coordination and adaptive implementation to ensure that vaccination complements and strengthens broader malaria elimination efforts.

Conclusion

Malaria remains a significant global health issue, demanding heightened attention and coordinated efforts for elimination, particularly in Africa, where the burden of the disease is highest. The development of vaccines marks a critical step toward malaria elimination, and routine vaccination can play a key role in controlling and eventually eliminating malaria in Africa. However, more efforts are required to scale up vaccine production to meet demand, while simultaneously strengthening healthcare infrastructure and systems to ensure effective vaccine distribution across the continent. Further research is essential to improve the efficacy of existing vaccines and develop more effective alternatives. These efforts should be complemented by the advancement of additional interventions, such as novel vector control strategies and therapeutic innovations, to support vaccines in achieving malaria elimination in Africa and eradication globally. Comprehensive, multi-faceted approaches will be necessary to fully address this complex public health challenge.

Abbreviations

WHO	World Health Organization
ITNs	Insecticide-treated bed nets
IRS	Indoor residual spraying
IPT	Intermittent preventive treatment
WRAIR	Walter Reed Army Institute of Research
CSP	Circumsporozoite protein
HBsAg	Hepatitis B virus surface protein
AMVIRA	Accelerating Malaria Vaccine Introduction and Rollout in Africa
MVIP	Malaria Vaccine Implementation Programme
ATSBs	Attractive toxic sugar baits
mAbs	Monoclonal antibodies
GIS	Geographic Information Systems

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Author contributions
O.S. conceptualized the study, designed the methodology, managed the project, provided resources, and contributed to writing the first draft, review and editing, and the final draft. J.B. validated the study, provided resources, and participated in writing the first draft, review, and final draft. S.A.S., M.G.U., and A.O. contributed resources and were involved in writing the first draft, review, and final draft. A.M.K. participated in the investigation, while S.O.D. also contributed to the investigation and writing. L.T.B. and B.G.A. contributed resources and participated in writing, while R.O.O. was involved in writing and editing. All authors reviewed the manuscript.

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Ethics approval and consent to participate
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Consent for publication
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Competing interests
The authors declare no competing interests.

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