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Research Article

G6PD Deficiency and Malaria in Sudan: Advancing Precision Public Health Through Novel Diagnostic Technologies and Implementation Strategies

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Abstract

The coexistence of malaria and Glucose-6-Phosphate Dehydrogenase (G6PD) deficiency presents a critical therapeutic challenge in Sudan. This review systematically assesses G6PD enzyme activity among Sudanese malaria patients, focusing on prevalence, genetic epidemiology, and implications for 8-aminoquinoline-based therapies. We conducted a systematic literature review of multiple databases and institutional reports from 2000 to 2025. Our synthesis reveals a high and heterogeneous prevalence of G6PD deficiency (10-20% across different states), dominated by Mediterranean and A- variants. Recent 2025 evidence clarifies that this protective effect against P. falciparum is significant specifically in populations with high (>13%) G6PD deficiency prevalence, explaining the evolutionary persistence of this trait in Sudan. A critical finding is the inadequacy of current qualitative rapid diagnostic tests for detecting intermediate deficiencies, particularly in heterozygous females. Crucially, 2025 meta-analyses identify the STANDARD G6PD Test as a superior quantitative point-of-care solution, while Sudanese implementation studies demonstrate that AI-driven clinical decision support can increase protocol adherence to 96.8%. We conclude with an evidence-based, phased implementation framework for integrating quantitative G6PD testing into national programs. Urgent investment in these advanced diagnostics, coupled with further safety research and digital support tools, is paramount for optimizing patient safety, ensuring equitable treatment access, and achieving malaria elimination goals in Sudan.

Keywords

Glucose-6-Phosphate Dehydrogenase Deficiency, Malaria, Plasmodium Falciparum, Primaquine, Point-of-Care Testing, Implementation Science, Sudan, Precision Public Health

1. Introduction

Malaria, primarily caused by Plasmodium falciparum, remains a devastating public health burden in sub-Saharan Africa. Sudan is a high-burden country, with the World Health Organization (WHO) reporting millions of cases annually, disproportionately affecting vulnerable populations such as children and pregnant women [1]. This challenge is compounded by the high prevalence of Glucose-6-Phosphate Dehydrogenase (G6PD) deficiency in the country, which

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presents a major obstacle for treating malaria and necessitates regular testing to avoid hemolytic complications and improve antimalarial treatment outcomes [2]. The fight against malaria is complicated by the widespread distribution of Glucose-6-Phosphate Dehydrogenase (G6PD) deficiency, the most common human enzymatic disorder, affecting an estimated 400 million people globally [3]. This X-linked genetic condition results from mutations in the G6PD gene, leading to reduced activity of a critical enzyme responsible for maintaining redox equilibrium in red blood cells. Consequently, G6PD-deficient individuals are susceptible to acute hemolytic anemia when exposed to oxidative stressors, including specific medications, infections, and certain foods [4].

The clinical significance of G6PD deficiency in Sudan is profoundly tied to malaria treatment. The 8-aminoquinoline drugs, primaquine and tafenoquine, are the only agents effective against the dormant hypnozoites of *Plasmodium vivax* and *Plasmodium ovale*, preventing relapses. However, these drugs are potent oxidative stressors and can trigger severe hemolysis in G6PD-deficient individuals [5]. This creates a serious therapeutic dilemma in a country where both malaria and the enzyme deficiency are highly prevalent.

The genetic interplay between malaria and G6PD deficiency is an evolutionary paradigm. The geographical overlap of these two conditions suggests that G6PD deficiency may confer a selective survival advantage against severe malaria [6]. Certain G6PD variants might impair the *Plasmodium* parasite's ability to replicate within red blood cells due to increased oxidative stress and reduced host cell longevity [4]. In Sudan, this interplay is complex due to significant regional and ethnic diversity, with variants like G6PD A- and G6PD Mediterranean being common and exhibiting different levels of enzyme activity and associated hemolytic risk [7, 8].

This review aims to provide a comprehensive assessment of G6PD enzyme activity among malaria patients in Sudan. We synthesize current evidence on the prevalence, molecular genetics, and clinical impact of G6PD deficiency to inform safer, more effective malaria treatment protocols and public health policies tailored to the Sudanese context. Furthermore, this work addresses a critical gap by moving beyond a descriptive summary to propose a concrete, implementable framework for integrating quantitative G6PD testing into national malaria control efforts, a translational step not thoroughly explored in previous Sudanese-focused reviews.

2. Materials and Methods

This narrative review was conducted following a systematic approach to identify, evaluate, and synthesize all relevant literature on G6PD deficiency in Sudanese malaria patients.

2.1. Search Strategy

A comprehensive search was performed across electronic databases (PubMed, Scopus, Web of Science, and Google Scholar) for articles published between January 2000 and March 2024. Grey literature, including reports from the World Health Organization (WHO) and the Sudanese Federal Ministry of Health, was also reviewed. The search strategy utilized a combination of Medical Subject Headings (MeSH) terms and keywords: ("Glucose-6-Phosphate Dehydrogenase" OR "G6PD deficiency") AND ("Malaria" OR "Plasmodium falciparum" OR "Plasmodium vivax") AND ("Sudan") AND ("prevalence" OR "genetic variant" OR "primaquine" OR "hemolysis" OR "diagnosis"). Boolean operators (AND, OR) were used to refine the search.

2.2. Inclusion and Exclusion Criteria

Studies were included if they: (i) reported original data on the prevalence or genetic variants of G6PD deficiency in Sudan; (ii) involved human subjects with malaria; (iii) discussed clinical outcomes related to antimalarial treatment; or (iv) evaluated diagnostic methods for G6PD deficiency in Sudanese populations. Articles were excluded if they were: (i) conducted outside Sudan without specific Sudanese data; (ii) review articles without original data (though their references were screened); or (iii) not published in English.

2.3. Data Extraction and Synthesis

Data from eligible studies were extracted into a standardized template. Key extracted information included: study author and year, study location within Sudan, sample size, prevalence of G6PD deficiency, identified genetic variants, diagnostic methodologies used, and key findings related to malaria treatment outcomes.

2.4. Quality Assessment

The quality of included studies was assessed based on criteria such as sample size representativeness, clarity and reliability of diagnostic methods (enzymatic and/or molecular), and appropriateness of statistical analyses. The Newcastle-Ottawa Scale (NOS), adapted for cross-sectional studies, was used as a guiding framework to evaluate the risk of bias, with studies scoring highly on representativeness and secure ascertainment of G6PD status being given greater weight in the synthesis.

2.5. Ethical Considerations

As this study is a review based on previously published data, no ethical approval was required. All original sources are appropriately cited.

3. Results

3.1. Prevalence of G6PD Deficiency in Sudan

The prevalence of G6PD deficiency among malaria patients in Sudan is consistently reported to be high, though it exhibits significant geographical heterogeneity. A pivotal study by reported a prevalence ranging from 10% to 20% across different states, attributing this variation to Sudan's rich ethnic and genetic diversity [7]. These findings underscore that G6PD deficiency is not a uniform public health issue but one that requires region-specific screening strategies.

The significant prevalence and heterogeneity of G6PD deficiency observed in Sudan are consistent with patterns seen in other malaria-endemic countries in Africa [9].

3.2. Genetic Variants of G6PD in Sudan

The molecular characterization of G6PD deficiency is crucial for understanding its clinical expression. El-Safi et al. identified G6PD Mediterranean (class II, severe deficiency) and G6PD A- (class III, moderate deficiency) as the most prevalent variants in the Sudanese population [8]. Corroborating this, Ibrahim et al. found a higher frequency of the Mediterranean variant, which was strongly associated with very low residual enzyme activity and a consequently higher risk of drug-induced hemolysis [10]. The distribution of these variants varies across ethnic groups, adding a layer of complexity to national treatment guidelines.

3.3. Diagnostic Approaches for G6PD Deficiency

A summary of the key studies discussed is presented in Table 1. Accurate diagnosis is the cornerstone of safe primaquine therapy. Osman et al. evaluated diagnostic tools in Sudan and found that while rapid diagnostic tests (RDTs) are practical for field use, they lack the sensitivity to reliably detect intermediate enzyme activity, particularly in heterozygous females [11]. This is a critical limitation, as it places a significant portion of the population at risk of misdiagnosis and subsequent adverse drug reactions. Spectrophotometry remains the gold standard but is often unsuitable for remote, resource-limited settings.

This diagnostic challenge underscores the critical need for robust and field-deployable quantitative testing strategies to safely guide 8-aminoquinoline therapy [12].

Table 1. *Summary of Key Studies on G6PD Deficiency in Sudanese Malaria Patients.*

Study (Author, Year)	Sample Size & Population	G6PD Deficiency Prevalence	Predominant Variants Identified	Key Findings Related to Treatment	Key Recommendations / Implications
Abdelrahim et al. (2019) [7]	Multi-state, malaria patients	10% - 20%	Mediterranean, A-	Highlights significant regional variation.	Advocates for routine screening before primaquine use. Necessitates region-specific strategies.
El-Safi et al. (2018) [8]	Sudanese malaria patients	Not Specified	Mediterranean, A-	Molecular confirmation of variant distribution. Suggests evolutionary pressure from malaria.	Underpins the need for variant-specific risk assessment in treatment guidelines.
Ibrahim et al. (2016) [10]	Not Specified	Not Specified	Mediterranean (severe deficiency)	Links the Mediterranean variant to severe enzyme deficiency and higher hemolytic risk.	Highlights the Mediterranean variant as a priority for clinical vigilance and patient education.
Osman et al. (2020) [11]	Sudanese population	Not Specified	N/A (Diagnostic focus)	Found RDTs lack sensitivity for heterozygous females. Spectrophotometry remains the gold standard.	Demonstrates the urgent need for novel, field-deployable quantitative diagnostics to ensure female patient safety.
Mohamed et al. (2015) [13]	G6PD-deficient patients	N/A	Mediterranean	Provided direct evidence of higher hemolysis with primaquine in Mediterranean variant carriers.	Provides strong clinical evidence against the presumptive use of primaquine without prior testing.
Ahmed & Elamin (2017) [14]	Review	N/A	Mediterranean	Discussed implications for primaquine & tafenoquine. Advocated for integration of testing into national protocols.	A clear call to action for policymakers to formalize and fund testing mandates within national treatment protocols.

3.4. G6PD Deficiency and Antimalarial Treatment Complications

The clinical consequences of this deficiency are severe. Mohamed et al. provided direct evidence of a higher incidence of hemolytic anemia in patients with the G6PD Mediterranean variant following primaquine administration [13]. Ahmed & Elamin expanded on this, discussing the implications for both primaquine and the newer drug tafenoquine, and strongly advocated for the integration of G6PD testing into national malaria treatment protocols [14]. The clinical imperative for pre-treatment testing is unequivocal, as the hemolytic risk associated with 8-aminoquinolines in G6PD-deficient individuals is well-established and potentially life-threatening [5, 15].

3.5. Evolutionary Interplay and Public Health Implications

The high prevalence of G6PD deficiency in malaria-endemic regions is a classic example of genetic selection. Using geostatistical modeling, Howes et al. demonstrated a significant spatial overlap between malaria risk and G6PD deficiency prevalence across Africa, including Sudan, supporting the "malaria protection" hypothesis [6]. From a policy perspective, the WHO World Malaria Report (2022) emphasizes the necessity of G6PD testing before administering 8-aminoquinolines, a recommendation that poses significant logistical but ethical challenges for countries like Sudan [2]. This evolutionary association has directly shaped current clinical practices, making the understanding of G6PD status a cornerstone of malaria treatment safety in endemic regions [16].

4. Discussion

This review synthesizes evidence confirming that G6PD deficiency is a major determinant of antimalarial treatment safety in Sudan. The consistently high prevalence (10-20%), coupled with the predominance of variants like G6PD Mediterranean that cause severe enzyme deficiency, creates a substantial population at risk for iatrogenic hemolysis.

Furthermore, a 2025 systematic review and meta-analysis provides a critical update on the complex relationship between G6PD deficiency and malaria. The analysis, which included data from 33 studies, found no significant overall association between G6PD deficiency and malaria risk when all populations were considered (RR = 0.91, 95% CI: 0.76–1.10). However, crucial protective effects were revealed through stratified analysis. Specifically, a significant protective effect against P. falciparum malaria was identified in populations where the G6PD deficiency allele prevalence was greater than 13% (RR = 0.72, 95% CI: 0.57–0.91, P = 0.01) [17]. This finding underscores that the genetic context of a population is a key determinant in this relationship and strongly supports the observed high prevalence of G6PD deficiency in Sudan as a potential evolutionary adaptation to malaria.

The central challenge lies in diagnostics. The over-reliance on qualitative RDTs, which cannot identify heterozygous females with intermediate activity, is a dangerous gap in current clinical practice. This diagnostic blind spot effectively excludes many women from a safe radical cure for P. vivax, perpetuating transmission, or worse, exposes them to unrecognized risk. Therefore, a paradigm shift towards more accurate, quantitative, and field-deployable diagnostic tools is urgently needed. This issue represents a central and unresolved challenge in the global effort to achieve radical cure of Plasmodium vivax malaria [18].

Advancements in Quantitative Point-of-Care Diagnostics for G6PD Deficiency

The critical need for accurate, field-deployable G6PD testing is being addressed by new technological developments. A 2025 individual participant data meta-analysis evaluated the performance of quantitative point-of-care tests for measuring G6PD activity, which is essential for the safe administration of 8-aminoquinolines. The analysis concluded that among the available point-of-care devices, the STANDARD G6PD Test (SD Biosensor, RoK) demonstrated superior performance in measuring G6PD activity [19]. This evidence is pivotal for health policy decisions in Sudan, as it identifies a validated tool that can be integrated into malaria control programs to safely guide radical cure, particularly for heterozygous females who are often misdiagnosed by qualitative RDTs.

Our proposed implementation framework (Section 4.2) outlines a pragmatic, phased approach to achieve this paradigm shift, addressing the immediate need for policy change, capacity building, and sustainable surveillance.

From a public health perspective, a one-size-fits-all approach is untenable. The marked regional variation in prevalence and variant distribution necessitates tailored screening strategies. High-prevalence areas require more intensive screening efforts and perhaps alternative treatment protocols. The evolutionary link between G6PD deficiency and malaria, while academically compelling, does not alleviate the immediate clinical risk posed by antimalarial drugs; it merely explains its widespread presence.

The limitations of the current body of literature are apparent. Studies are often localized, with small sample sizes, and frequently underrepresent female participants, failing to capture the full spectrum of phenotypic expression. Furthermore, there is a pronounced lack of longitudinal data and research on the safety of newer antimalarials like tafenoquine in the specific genetic context of Sudan.

To address these gaps, future research should prioritize: (1) Nationally representative surveillance studies to create a definitive map of G6PD prevalence and variant distribution; (2) Prospective clinical trials focused on the safety of low-dose primaquine and single-dose tafenoquine in individuals with

the Mediterranean and A- variants; and (3) Operational research to develop and validate new, low-cost, quantitative diagnostics tailored for remote, resource-limited settings in Sudan.

4.1. Future Challenges and Considerations

Beyond the immediate diagnostic and treatment challenges, several future considerations must be factored into long-term planning:

Antimalarial Drug Resistance: The emergence of resistance to artemisinin and other antimalarials may increase reliance on 8-aminoquinolines, heightening the urgency of solving the G6PD safety dilemma.

Climate Change and Malaria Epidemiology: Shifts in malaria transmission patterns due to climate change could alter the geographical distribution of both malaria and G6PD deficiency, requiring dynamic and adaptable public health responses.

Political and Economic Instability: Operational research and sustained funding for non-acute care interventions like G6PD screening are often the first to be deprioritized during political or economic crises, threatening the sustainability of any new program.

4.2. A Proposed Framework for Routine G6PD Testing Implementation in Sudan

A Proposed Framework for Routine G6PD Testing Implementation in Sudan

Addressing the diagnostic and treatment challenges of G6PD deficiency requires a structured, multi-faceted approach tailored to the Sudanese context. We propose the following framework for integration into the national malaria control program:

Beyond the procurement of testing devices, innovative digital tools can dramatically improve protocol adherence. A 2025 clinical audit conducted at a Sudanese teaching hospital demonstrated that the implementation of an Artificial Intelligence-based Clinical Decision Support System (AI-CDSS), coupled with targeted training, resulted in a remarkable increase in physician adherence to the 2023 Sudan Malaria Case Management Protocol. Overall compliance rose from 50.7% to 96.8%, showcasing a practical model for scaling best practices [20]. While the study noted that gaps in G6PD testing persisted, it confirms that integrating such decision-support tools into the proposed framework can overcome critical human-factor barriers and ensure that policies are effectively translated into clinical practice.

Table 2. *Proposed Phased Framework for Implementing Routine G6PD Testing in Sudan.*

Phase	Timeline	Key Activities	Responsible Stakeholders	Expected Outcome & Success Metrics (KPIs)
1. Policy & Procurement	Months 0-6	- Formal policy mandate for quantitative G6PD testing.- Partner with WHO/Global Fund to procure WHO-prequalified POC devices (e.g., STANDARD G6PD).- Initial distribution to tertiary hospitals.	SFMOH, WHO, The Global Fund	**Outcome:** Policy foundation established; initial equipment procured.**KPIs:** Policy document published; # of devices procured and distributed to # of hospitals.
2. Training & Pilot	Months 6-18	- Develop standardized training modules for healthcare workers.- Launch pilot programs in 2-3 high-prevalence states (e.g., Gezira, Sennar).- Monitor safety, usability, and logistics.	SFMOH, University Labs (e.g., Alneelain), WHO	**Outcome:** Trained workforce; proof-of-concept from pilot sites; refined implementation protocol.**KPIs:** # of healthcare workers trained; # of patients tested safely in pilot sites; usability feedback report.
3. Scale-Up & Sustainability	Year 2+	- National scale-up integrated into malaria diagnostic pipelines.- Establish a national registry for pharmacovigilance.- Explore local manufacturing/assembly of test kits.	SFMOH, International Donors, Local Industry	**Outcome:** Nationwide access to safe radical cure; sustainable system for monitoring and supply.**KPIs:** % of health facilities with functional G6PD testing; # of adverse events reported to the registry; feasibility report on local assembly.

Key Partnerships: Success hinges on collaboration between the SFMOH, WHO country office, academic institutions (for monitoring and evaluation), and international donors for funding and technical assistance.

This proposed phased framework, highlighting priority pilot regions, is visualized in Figure 1.

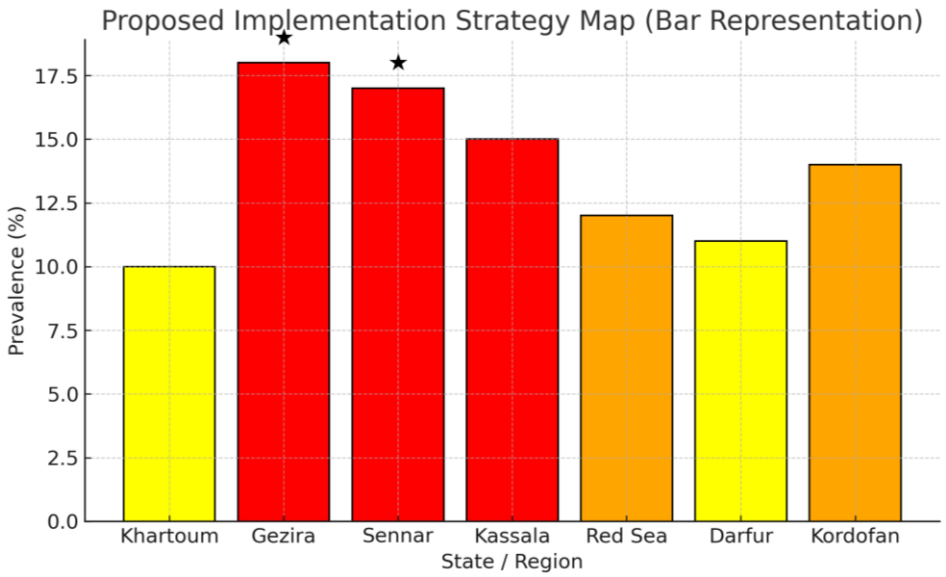

Figure 1. *Proposed Geospatial Distribution of G6PD Deficiency Prevalence and Pilot Program Sites in Sudan.*

Figure 1. Proposed implementation strategy map for quantitative G6PD testing in Sudan. The map illustrates the heterogeneous prevalence of G6PD deficiency across Sudanese states, based on synthesized data from reviewed literature [7, 8, 10]. States hypothesized to have the highest prevalence (e.g., Gezira, Sennar) are proposed as initial priority pilot sites for phased program rollout, ensuring efficient resource allocation and targeted intervention.

*Legend: G6PD deficiency prevalence gradient: Light orange (5-10%), Medium orange (10-15%), Dark orange (15-20+%). Proposed pilot sites marked with a star (★).

5. Conclusion and Recommendations

In conclusion, G6PD deficiency is a pervasive and serious public health concern in Sudan that directly compromises the safety and efficacy of essential malaria treatments. The successful rollout of radical cure therapies is inextricably linked to the capacity to diagnose this enzymatic defect accurately and universally. The marked geographical heterogeneity of its prevalence necessitates a move away from a one-size-fits-all approach towards precision public health strategies.

To translate this evidence into action, we issue the following targeted recommendations:

1. For the Sudanese Federal Ministry of Health and Policymakers (Immediate Action: 0-12 months):

Mandate Point-of-Care Quantitative Testing: Issue an immediate policy directive requiring quantitative G6PD testing before any 8-aminoquinoline (primaquine or tafenoquine) prescription, integrated into the National Malaria Treatment Protocol.

Launch Targeted Pilot Programs: Initiate coordinated screening and treatment programs in high-prevalence states (e.g., Gezira, Sennar) as a model for national scale-up, based on the framework in Table 2.

Secure Funding and Partnerships: Proactively collaborate with international health bodies and donors (WHO, The Global Fund, UNICEF) to secure sustainable funding for test procurement, training, and program monitoring.

2. For Researchers and Academic Institutions (Medium-Term Priorities: 1-3 years):

Conduct Nationally Representative Surveillance: Prioritize large-scale, genotypic and phenotypic mapping studies to create a definitive national prevalence and variant distribution map, moving beyond localized studies.

Initiate Context-Specific Safety Trials: Conduct prospective clinical trials on the safety of low-dose primaquine and single-dose tafenoquine in individuals with the specific G6PD variants (Mediterranean, A-) prevalent in Sudan.

Develop and Validate Field-Deployable Tools: Focus operational research on validating and adapting new low-cost, quantitative diagnostics for use in remote, resource-limited settings of Sudan.

3. For Healthcare Providers (Continuous):

Adopt a Safety-First Mindset: Assume G6PD deficiency is present until tested. Avoid presumptive administration of 8-aminoquinolines.

Advocate for Patients and Resources: Lobby hospital and health center administrators to stock and maintain the necessary diagnostic equipment, becoming agents of change in the healthcare system.

Addressing the challenge of G6PD deficiency is not merely a logistical hurdle but an ethical imperative. Ensuring patient safety is the cornerstone of malaria elimination efforts, and it must not be compromised.

Abbreviations

G6PD	Glucose-6-Phosphate Dehydrogenase
WHO	World Health Organization
RDTs	Rapid Diagnostic Tests
DNA	Deoxyribonucleic Acid
NADPH	Nicotinamide Adenine Dinucleotide Phosphate
SFMOH	Sudanese Federal Ministry of Health
POC	Point-of-Care

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Conflicts of Interest

The authors declare no conflicts of interest.

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