IAA Journal of Scientific Research 13(1):71-77, 2026. www.iaajournals.org

©IAAJOURNALS ISSN: 2636-7319

https://doi.org/10.59298/IAAJSR/2026/1317177 IAAJSR:1311

Efficacy of Insecticide-Treated Nets and Community Strategies in Malaria Prevention during Pregnancy

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ABSTRACT

Malaria during pregnancy constituted a major public health challenge in endemic regions, causing maternal anemia, placental infection, low birth weight, and increased perinatal mortality. Pregnant women exhibit increased susceptibility due to immunological changes and placental sequestration of Plasmodium falciparum-infected erythrocytes. Insecticide-treated nets represent a cornerstone intervention for malaria prevention, while community-based strategies complement vector control through education, early diagnosis, and treatment accessibility. This review evaluated the efficacy of insecticide-treated nets and community-level interventions in preventing malaria during pregnancy, examining their impact on parasitemia rates, maternal outcomes, and birth outcomes across diverse transmission settings. A comprehensive analysis of evidence examining the effectiveness of insecticide-treated nets, community health worker programs, the integration of intermittent preventive treatment, and behavioral interventions for malaria prevention in pregnant populations was conducted. Insecticide-treated nets reduced malaria infection during pregnancy by 30 to 50 percent and improved birth weight outcomes, with long-lasting insecticidal nets demonstrating sustained effectiveness over multiple years. Community health worker programs enhanced antenatal care attendance, improved net utilization rates, and facilitated early case detection, with coverage rates exceeding 70 percent in well-implemented programs. However, insecticide resistance, net durability under field conditions, and equity of distribution presented implementation challenges. Community strategies demonstrated variable effectiveness depending on health system integration, worker training quality, and sustained funding. Combined deployment of insecticide-treated nets with comprehensive community interventions provided synergistic protection against pregnancy-associated malaria, though addressing operational barriers and insecticide resistance remained critical for sustained impact.

Keywords: Pregnancy malaria, Insecticide-treated nets, Community health workers, Vector control, Maternal outcomes

INTRODUCTION

Insecticide-treated nets function through dual mechanisms: physical barrier prevention of mosquito-human contact and chemical killing or repelling of vector mosquitoes through synthetic pyrethroid insecticides incorporated into net fibers [1, 2]. Long-lasting insecticidal nets represent technological advances with insecticide either coated onto fibers or incorporated within fiber polymers, providing effective protection for three to five years under field conditions [3, 4]. Pyrethroid insecticides, including permethrin, deltamethrin, and alpha cypermethrin, bind to voltage-gated sodium channels in mosquito nervous systems, causing knockdown and mortality following brief contact. The spatial repellent effects extend protection beyond net users, creating community-level transmission reduction when coverage reaches sufficient thresholds. Net efficacy depends on multiple factors, including insecticide concentration and retention, net integrity maintained through proper handling and repair, sleeping arrangements ensuring complete body coverage, and consistent nightly use, particularly during peak biting hours. Mosquito behavioral adaptations, including earlier biting times and outdoor feeding, potentially circumvent net protection, though nets remain highly effective against predominantly nocturnal indoor feeding Anopheles vectors transmitting

malaria. Insecticide resistance, particularly metabolic resistance mechanisms and target site mutations such as kdr alleles in voltage-gated sodium channel genes, threatens long term net effectiveness across malaria endemic regions. Pregnancy induces profound immunological alterations characterized by T helper 2 cytokine profile shifts, regulatory T cell expansion, and localized immune suppression at the maternal-fetal interface to maintain fetal tolerance [5]. These changes increase susceptibility to intracellular pathogens, including Plasmodium species, with pregnant women experiencing higher infection rates, increased parasite densities, and greater risk of severe disease compared to non-pregnant women. Placental malaria develops through preferential sequestration of infected erythrocytes expressing variant surface antigens, particularly VAR2CSA binding chondroitin sulfate A on placental syncytiotrophoblasts [6]. Primigravidae demonstrate the highest vulnerability due to absent immunity to pregnancy-specific parasite variants, while multigravidae develop protective antibodies, reducing infection severity. Placental inflammation triggered by sequestered parasites impairs nutrient transfer, induces oxidative stress, and disrupts angiogenic balance, resulting in intrauterine growth restriction and low birth weight. Maternal anemia develops through hemolysis, dyserythropoiesis, and increased iron requirements, contributing to maternal mortality and poor fetal outcomes. Community strategies encompassing health education, trained community health workers providing antenatal screening and treatment, accessible diagnostic and therapeutic services, and behavior change communication enhance facility-based interventions by addressing geographical, cultural, and economic barriers to care access. This review critically synthesizes evidence on insecticide-treated net efficacy and community-based intervention strategies for malaria prevention during pregnancy, evaluating their impact on infection rates, maternal health, and birth outcomes.

Biological Efficacy and Protective Mechanisms of Insecticide-Treated Nets in Pregnancy

Insecticide-treated nets confer protection through multiple interconnected mechanisms operating at individual and community levels to reduce malaria transmission during pregnancy [7]. At the individual level, intact nets create a physical barrier preventing mosquito contact with pregnant women during sleep, the primary period of Anopheles vector feeding activity in most endemic settings. Pyrethroid insecticides impregnated in net fibers provide additional chemical protection, repelling host-seeking mosquitoes before blood-feeding attempts and causing rapid knockdown mortality upon contact with treated surfaces [8]. Experimental hut studies demonstrate that long-lasting insecticidal nets kill 40 to 80 percent of entering mosquitoes and deter substantial proportions from entering sleeping spaces [9, 10], with mortality rates varying by insecticide concentration, mosquito species susceptibility, and environmental factors affecting insecticide degradation. Pregnant women produce greater quantities of volatile organic compounds and carbon dioxide due to increased metabolic rates and body surface area, rendering them more attractive to mosquitoes and amplifying the protective value of net usage during gestation.

Field studies in Sub Saharan African populations document that consistent insecticide-treated net use during pregnancy reduces peripheral and placental parasitemia by 30 to 50 percent compared to non-users [11], with protective efficacy varying by transmission intensity and background immunity. In high transmission settings where pregnant women possess some baseline immunity from childhood exposures, nets primarily prevent high-density infections and clinical malaria episodes rather than all infections. Conversely, in low to moderate transmission areas where pregnant women lack substantial acquired immunity, nets demonstrate higher efficacy against infection acquisition. Placental malaria prevalence decreases by 20 to 35 percent among net users, with corresponding reductions in placental inflammation, syncytial damage, and immune cell infiltration observed in histopathological examinations [12, 13]. The protective effect appears greatest for primigravidae and secundigravidae who lack pregnancy-specific immunity, achieving up to 50 percent reduction in placental infection compared to more modest 15 to 25 percent reductions in multigravidae.

Community-level protection emerges when insecticide-treated net coverage exceeds 40 to 50 percent of households, reducing overall vector populations and infection prevalence even among non-net users through mass killing of mosquitoes attempting to feed on protected individuals [14]. Mathematical modeling and observational studies demonstrate nonlinear relationships between coverage and protection, with disproportionate benefits accruing above threshold coverage levels. However, insecticide resistance significantly compromises net effectiveness, with mosquito populations carrying kdr mutations or elevated metabolic enzyme activity demonstrating reduced mortality following net contact. Areas with high frequency pyrethroid resistance alleles show 20 to 40 percent lower protective efficacy compared to fully susceptible vector populations, though nets retain some protective value through physical barrier and irritancy effects. These biological efficacy data underscore the importance of maintaining high coverage, ensuring net integrity, and developing next-generation tools addressing insecticide resistance to sustain protection.

Impact of Insecticide-Treated Nets on Maternal and Birth Outcomes

Insecticide-treated net usage during pregnancy translates biological efficacy against malaria infection into measurable improvements in maternal health status and birth outcomes, though effect magnitudes vary across transmission settings and population immunity profiles [15]. Maternal anemia, defined as hemoglobin concentrations below 11 grams per deciliter during pregnancy, decreases by 15 to 30 percent among consistent net

users compared to non-users in high transmission areas, with mean hemoglobin concentrations approximately 0.3 to 0.5 grams per deciliter higher [16]. This hematological benefit reflects reduced malaria associated hemolysis, improved iron utilization, and decreased inflammation induced dyserythropoiesis. Severe anemia requiring transfusion occurs less frequently in net-using populations, reducing maternal morbidity and transfusion-associated risks. Clinical malaria episodes during pregnancy decrease by 40 to 60 percent with net use, lowering risks of hospitalization, severe disease complications, and treatment-related adverse effects. Pregnant women using nets report fewer symptomatic illnesses, reduced absenteeism from work or household duties, and lower healthcare expenditures, providing economic benefits complementing health improvements.

Birth weight outcomes demonstrate consistent improvements associated with maternal net use during pregnancy, with meta-analyses documenting mean increases of 50 to 100 grams in offspring of net users [17]. Low birth weight, classified as weight below 2500 grams, occurs 15 to 25 percent less frequently among infants born to mothers using nets throughout pregnancy. These effects appear mediated primarily through prevention of placental malaria and maternal anemia, as analyses restricted to malaria-free pregnancies show attenuated or absent birth weight benefits. Primigravidae experience larger birth weight improvements, averaging 80 to 150 grams, compared to multigravidae with 30 to 60 gram increases, paralleling differential placental malaria risk patterns. Gestational age at delivery shows modest improvements, with approximately 10 to 20 percent reduction in preterm birth rates, though effects are less consistent across studies than birth weight impacts [18]. Perinatal and neonatal mortality decrease by 15 to 30 percent in high transmission settings with high net coverage, representing substantial public health benefits given the large absolute burden.

Effect modification by transmission intensity, seasonality, and concurrent interventions complicates the interpretation of net impact on pregnancy outcomes across settings. High transmission perennial malaria areas demonstrate larger absolute risk reductions but smaller relative effects compared to seasonal or low transmission settings where baseline risks are lower. Integration of intermittent preventive treatment with sulfadoxine pyrimethamine alongside net use produces additive or synergistic benefits, with combined interventions achieving superior outcomes to either alone [19]. However, studies inadequately controlling for socioeconomic factors, healthcare access, and other determinants of birth outcomes may overestimate net specific effects. Long-term follow-up studies examining child development outcomes remain limited, though available data suggest neurodevelopmental benefits paralleling improvements in birth weight and reductions in severe malaria exposure during pregnancy, highlighting the importance of protecting pregnant women from malaria as a life course intervention.

Community-Based Distribution and Utilization Enhancement Strategies

Community-level interventions enhance insecticide-treated net coverage and utilization through distribution systems reaching populations with limited health facility access, behavioral strategies promoting consistent use, and integrated service delivery addressing multiple maternal and child health priorities. Community health worker programs train and deploy residents to provide health education, distribute nets, conduct household visits monitoring net condition and usage, and facilitate referrals for antenatal care and malaria treatment [20]. Evidence from multiple countries demonstrates that community health workers delivered net distribution achieves 70 to 90 percent coverage of pregnant women compared to 40 to 60 percent coverage through facility-based distribution alone, particularly benefiting rural and underserved populations [21, 22]. Home visits by trained workers increase net utilization rates from a typical 50 to 60 percent in communities receiving nets without behavioral support to 75 to 85 percent with intensive education and follow-up, addressing barriers including misconceptions about net safety during pregnancy, discomfort in hot climates, and improper hanging techniques.

Mass distribution campaigns delivering free nets to all households, often timed with immunization programs or community events, rapidly achieve high population coverage but demonstrate variable sustainability without complementary maintenance and replacement systems. Studies comparing free distribution versus subsidized or full cost approaches consistently demonstrate superior equity and coverage with free provision, though cost recovery models may enhance perceived value and responsible use in some contexts. Integration of net distribution with antenatal care services, including provision during first antenatal visits and repeated reinforcement at subsequent contacts, leverages existing health system touchpoints and achieves coverage rates of 60 to 80 percent among women attending care [23]. However, reaching women with limited or late antenatal care attendance, including adolescents and marginalized populations, requires supplementary community-based approaches.

Behavioral change communication interventions addressing cultural beliefs, promoting the benefits of net use, and providing practical guidance on proper installation and maintenance demonstrate effectiveness in increasing consistent utilization. Participatory community dialogue sessions involving pregnant women, family members, and community leaders achieve greater acceptance and sustained behavior change compared to didactic education alone. Male partner engagement interventions recognizing household decision-making dynamics increase net acquisition and use, particularly in settings where men control economic resources. Text message reminders and mobile health

platforms providing pregnancy-specific malaria prevention information show promise in connected populations, though infrastructure and literacy limitations constrain reach in many high-burden settings.

Challenges compromising community strategy effectiveness include inadequate health worker training and supervision, irregular net replacement leading to coverage erosion over time, stockouts of supplies, and insufficient integration with health systems, limiting referral completion and quality of care. Community health worker retention and motivation depend on appropriate compensation, ongoing training opportunities, and recognition within health systems, with volunteer models demonstrating high attrition rates, compromising program sustainability [24]. Monitoring and evaluation systems tracking coverage, utilization, and health outcomes remain inadequate in many programs, precluding adaptive management and accountability. These operational realities underscore the importance of sustained investment, systems strengthening, and rigorous implementation research alongside efficacy studies.

Integration with Intermittent Preventive Treatment and Comprehensive Antenatal Services

Insecticide-treated nets function optimally within comprehensive malaria prevention strategies integrating intermittent preventive treatment, prompt diagnosis and treatment of breakthrough infections, and quality antenatal care addressing multiple health priorities during pregnancy [25]. Intermittent preventive treatment with sulfadoxine pyrimethamine, administered at scheduled antenatal visits regardless of infection status, provides complementary protection to nets by clearing existing infections and providing post treatment prophylaxis. Studies examining combined interventions demonstrate additive benefits, with net use plus at least two intermittent preventive treatment doses reducing placental malaria by 50 to 70 percent compared to 25 to 40 percent with either intervention alone. Birth weight improvements similarly show synergistic effects, suggesting that preventing both mosquito exposure and treating subclinical infections addresses complementary pathogenic pathways.

However, sulfadoxine pyrimethamine resistance threatens intermittent preventive treatment effectiveness across East and Southern Africa, with quintuple mutant parasites demonstrating treatment failure rates exceeding 40 percent [26]. Alternative regimens including dihydroartemisinin piperaquine show superior efficacy in high resistance settings and extended prophylactic protection, though higher costs and more complex dosing present implementation challenges. The relative contribution of nets versus intermittent preventive treatment to overall protection varies by resistance prevalence, with nets assuming greater importance as drug resistance increases. Modeling studies suggest that high-quality net programs may partially compensate for reduced intermittent preventive treatment efficacy, supporting prioritization of net distribution even in resource-constrained settings requiring difficult allocation decisions.

Integration of malaria prevention with broader antenatal services, including HIV testing and prevention, nutrition supplementation, tetanus immunization, and hypertension screening, improves efficiency and service uptake through one-stop delivery [27, 28]. Pregnant women receiving integrated services demonstrate higher retention in antenatal care and better adherence to multiple interventions compared to fragmented vertical programs. Community health workers trained in comprehensive maternal health, rather than a single disease focus, achieve better population health outcomes and cost-effectiveness. However, integration requires careful attention to avoiding overwhelming health workers with excessive tasks, maintaining quality across multiple service components, and ensuring adequate training for expanded responsibilities.

Early pregnancy detection and antenatal care initiation, facilitated through community awareness and screening programs, maximizes malaria prevention impact by enabling net provision and intermittent preventive treatment administration before placental infection establishment. Women initiating care during the first trimester demonstrate lower placental malaria rates and better birth outcomes compared to late presenters, highlighting the importance of community strategies promoting early care seeking. Adolescent pregnant women, who experience particularly high malaria and adverse outcome risks, benefit from targeted community outreach and youth-friendly services addressing their unique needs and barriers. These findings emphasize that technological interventions like nets require a supportive health system and community environments to realize full potential, with isolated deployment unlikely to achieve optimal impact.

Evidence Gaps, Implementation Challenges, and Future Research Priorities

Despite substantial evidence supporting insecticide-treated net efficacy for pregnancy malaria prevention, critical knowledge gaps and implementation challenges constrain optimization of programs and sustainability of impact. Insecticide resistance dynamics and their precise impact on net effectiveness in pregnant populations require further investigation, as most resistance studies focus on general populations without pregnancy-specific subgroup analyses. The threshold resistance levels at which nets lose clinically meaningful protective effects remain uncertain, complicating decisions about continued pyrethroid-only net distribution versus transition to higher cost next generation nets incorporating synergists or alternative insecticide classes. Dual active ingredient nets combining pyrethroids with piperonyl butoxide synergists or pyriproxyfen demonstrate superior entomological efficacy against resistant mosquitoes in experimental settings, though evidence for improved pregnancy and birth outcomes compared to standard long-lasting insecticidal nets remains limited, and cost effectiveness is uncertain.

Net durability under actual use conditions varies substantially across settings, with physical damage through tearing, burn holes, and seam separation compromising protective integrity often within two years despite a three-to-five-year design life. Factors influencing durability, including housing quality, household behaviors, and environmental conditions, require a better understanding to inform net design improvements and replacement schedules. Pregnant women may treat nets more carefully than the general populations given awareness of vulnerability, but evidence on differential durability remains sparse [29]. Optimal timing of net distribution during pregnancy, whether at first antenatal contact, during the second or third trimester, or pre-pregnancy among women of reproductive age, lacks definitive evidence, with tradeoffs between early protection initiation and net lifespan extending into subsequent pregnancies.

Community health worker program designs demonstrate enormous heterogeneity in training intensity, supervision frequency, compensation models, and scope of responsibilities, yet comparative effectiveness research identifying optimal configurations remains limited [30]. The relative benefits of specialist community health workers focused exclusively on malaria versus generalist workers addressing multiple maternal and child health issues require rigorous evaluation across diverse settings. Digital health innovations including mobile applications supporting community health worker decision making, electronic data capture improving monitoring, and direct to consumer messaging promoting behavior change show promise but need evaluation for effectiveness, cost, and equity impacts. [31] Male partner involvement strategies lack standardization and evidence regarding active ingredients driving effectiveness versus those representing resource intensive but inert program components.

Climate change impacts on malaria transmission patterns, potentially expanding geographic range and seasonality, necessitate adaptive strategies for net distribution and community interventions targeting shifting high risk areas and populations [32, 33]. Pregnant migrant and mobile populations including agricultural workers and refugees present unique challenges for intervention delivery and outcome monitoring, requiring innovative approaches ensuring equitable protection. Socioeconomic and gender equity dimensions of net access and utilization need greater research attention, as interventions may inadvertently widen disparities without deliberate efforts ensuring marginalized populations receive comparable benefits. Long term sustainability of free net distribution programs amid competing health priorities and constrained budgets requires economic evaluation documenting cost effectiveness and return on investment arguments supporting continued funding allocation to pregnancy focused malaria prevention [34].

CONCLUSION

Insecticide treated nets constitute highly effective tools for malaria prevention during pregnancy, reducing infection rates by 30 to 50 percent and improving maternal hemoglobin concentrations and birth weight outcomes across diverse transmission settings. Long lasting insecticidal nets provide sustained protection over multiple years with proper maintenance, though insecticide resistance and net physical deterioration threaten long term effectiveness. Community based distribution and behavioral promotion strategies significantly enhance net coverage and consistent utilization, achieving rates exceeding 70 percent when implemented with adequate training, supervision, and resources. Community health worker programs effectively reach underserved populations, integrate malaria prevention with comprehensive antenatal services, and facilitate early detection and referral of complications. Integration of nets with intermittent preventive treatment produces synergistic benefits superior to either intervention alone, though drug resistance increasingly compromises chemoprevention effectiveness. Evidence quality varies substantially across outcomes and settings, with robust data supporting impacts on parasitemia and birth weight contrasted against limited evidence for mortality effects, long-term child-development outcomes, and optimal program implementation approaches. Implementation challenges including insecticide resistance management, ensuring equitable access, maintaining net quality and coverage over time, and sustaining community health worker programs with adequate support require ongoing attention. Knowledge gaps regarding net durability, community intervention optimization, and adaptive strategies for changing epidemiology necessitate continued research alongside program implementation. The synergistic deployment of insecticide treated nets with comprehensive community strategies offers substantial potential for reducing pregnancy associated malaria burden when supported by strong health systems, sustained funding, and evidence-based program management. National malaria control programs should prioritize universal coverage of pregnant women with long lasting insecticidal nets through integrated community and facility-based distribution systems while establishing routine monitoring of insecticide resistance, net durability, and coverage equity to enable adaptive management sustaining intervention effectiveness.

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CITE AS: Mutebi Mark (2026). Efficacy of Insecticide-Treated Nets and Community Strategies in Malaria Prevention During Pregnancy. IAA Journal of Scientific Research 13(1):71-77. https://doi.org/10.59298/IAAJSR/2026/1317177