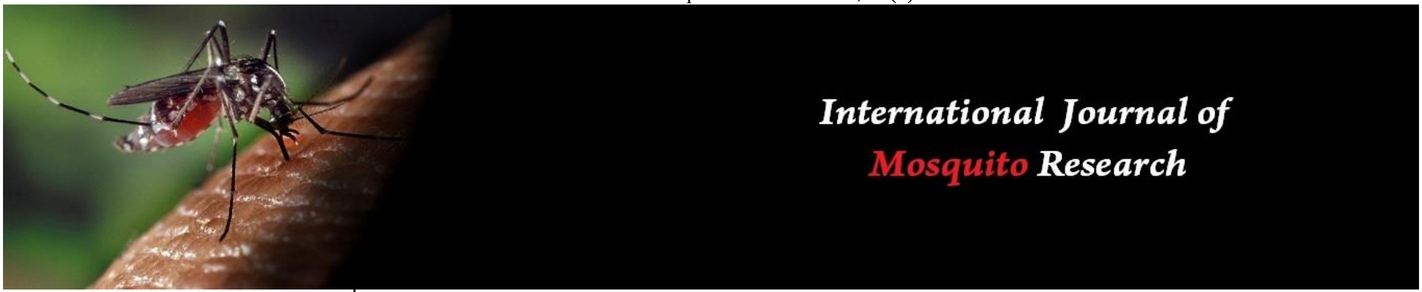

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Influence of irrigation systems on the seasonal persistence of malaria vector mosquitoes in Africa: Synthesis of ecological mechanisms

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Abstract
The expansion of irrigation systems in sub-Saharan Africa significantly alters landscapes, promoting the seasonal persistence of malaria vector mosquitoes (Anopheles spp.). This review analyzes the key ecological mechanisms driving this phenomenon. Developments like rice fields and gravity-fed canals create permanent or semi-permanent larval habitats, maintaining high mosquito densities even during the dry season. Irrigation modifies the local microclimate: increased humidity and attenuated thermal extremes extend adult survival. Furthermore, aquatic vegetation offers refuge and food for immature stages. Associated agricultural practices, including the use of fertilizers and pesticides, influence water quality and may select for resistant populations. These factors establish "wet islands" that sustain off-season malaria transmission. Understanding these interactions is vital for developing integrated management strategies that balance agricultural productivity with reduced vector risk. The article stresses the necessity of a multi-sectoral approach (agriculture, health, environment) for sustainable irrigation compatible with malaria control efforts.

Keywords: Irrigation, anopheles, vector ecology, seasonal persistence, malaria, Africa

Introduction

Malaria remains one of the most significant vector-borne diseases in sub-Saharan Africa, representing a major burden for public health and socioeconomic development [1]. According to the World Health Organization (WHO, 2023), more than 90% of global malaria cases occur on this continent, where human populations are exposed to vectors such as *Anopheles gambiae s.l.*, *An. funestus*, and *An. arabiensis* [2]. Malaria transmission is closely linked to the ecological dynamics of these mosquitoes, which depend on local environmental factors such as temperature, humidity, rainfall, and, above all, the availability of aquatic habitats favorable to larval development [3]. In this context, hydraulic infrastructures and agricultural irrigation systems play a decisive role in modulating the density and seasonality of vector mosquito populations [4].

Irrigation systems, including rice fields, gravity-fed irrigation perimeters, diversion canals, and localized irrigation networks, modify the availability and permanence of aquatic habitats [5]. Unlike natural ecosystems, where larval proliferation is often limited to the rainy season, irrigated environments can maintain suitable conditions throughout the year, creating “wet islands” that promote larval survival and adult mosquito maturation [6]. These changes affect not only vector density but also the species composition of *Anopheles* populations, their feeding behavior, and their interactions with human and animal hosts [7].

Scientific evidence indicates that the presence of permanent or semi-permanent aquatic habitats in irrigated areas can prolong the malaria transmission season, reducing the natural seasonality observed in non-irrigated zones [8]. Moreover, the concomitant use of fertilizers and agricultural insecticides can alter water quality and larval habitat suitability, sometimes selecting for mosquitoes resistant to insecticides used in vector control programs [9]. These complex interactions between hydraulic infrastructure, agricultural practices, and vector ecology underline the necessity of adopting an integrated management approach for irrigated landscapes [10].

This review aims to examine the influence of various irrigation systems on the seasonal persistence of malaria vector mosquitoes in Africa. It highlights the underlying ecological mechanisms, entomological patterns observed in field studies, and implications for public health and malaria control planning. The objective is to provide a scientific foundation for guiding integrated irrigation management that reduces malaria risk in irrigated agricultural zones.

2. Materials and methods

This synthesis is based on a systematic and analytical documentary review aimed at identifying, comparing, and interpreting available data on the relationship between agricultural irrigation and the ecology of malaria vector mosquitoes in Africa. The methodological approach proceeded in three main steps: documentary research, selection and critical analysis of studies, and thematic structuring of results.

2.1. Documentary rearch

The search for sources was conducted between January and September 2025 using international scientific databases (PubMed, Scopus, ScienceDirect, Web of Science, ResearchGate, and Google Scholar). The keywords used, alone or combined with Boolean operators, included: irrigation systems, rice fields, *Anopheles*, malaria vectors, seasonal persistence, Africa, entomology, ecological mechanisms, resistance, and environmental modification.

Articles published between 2000 and 2025 were considered, with particular attention to field **studies**, hydrological experiments, and entomological modeling analyses conducted in sub-Saharan Africa. Reports from international organizations (WHO, FAO, CILSS) were also consulted to complement contextual data.

2.2. Selection and analysis criteria

The publications selected met three criteria:

1. The presence of original data on the effect of irrigation on the biology, density, or seasonality of Anopheles mosquitoes;
2. The location of the study in an African tropical or semi-arid context;
3. The description of at least one ecological or agronomic parameter related to water management, cropping practices, or input use.

Each article was examined according to a summary reading grid, compiling information on the type of irrigation system, the entomological methodology used (trapping, larval surveys, entomological indices), the study period, the species observed, and the main results.

2.3. Data structuring and synthesis

The extracted information was grouped and analyzed according to a thematic approach to identify the recurrent ecological mechanisms by which irrigation influences mosquito dynamics. The results were organized into four axes:

1. Typology of irrigation systems and characteristics of larval habitats;
2. Local microclimatic and ecological modifications;
3. Entomological trends and seasonal persistence;
4. Management strategies and mitigation measures.

This structure allowed for the derivation of comparative patterns between irrigated and non-irrigated areas, as well as correlations between hydrological parameters, agricultural practices, and vector productivity.

2.4. Limitations and validity

This review is not a quantitative meta-analysis, but a qualitative and interpretive synthesis based on the convergent trends in the literature. Methodological differences between studies (trap types, sampling frequencies, ecological contexts) were considered in the interpretation of results. The most recent references (2020-2025) were prioritized to update knowledge, particularly in relation to climate change, insecticide resistance, and biocontrol practices.

3. Results & discussion

3.1. Types of irrigation systems and influence on larval habitats

Irrigation systems are a key factor in the ecological dynamics of malaria vector mosquitoes [11]. In sub-Saharan Africa, the expansion of irrigated agriculture aims to improve food security, but these developments profoundly alter local environmental conditions and create permanent or semi-permanent aquatic habitats conducive to the larval development of *Anopheles* mosquitoes [12]. The nature, design, and management of these systems determine the extent of their impact on vector density and the seasonal persistence of populations [13].

3.1.1. Rice fields

Rice fields (paddy fields) constitute one of the most studied irrigation types in the context of malaria transmission [14]. These crops require temporary or permanent field flooding, creating calm, shallow bodies of water. These conditions are particularly favorable for the larvae of *Anopheles gambiae s.l.* and other species within the *Anopheles funestus* complex [15]. Studies conducted in Mali, Burkina Faso, and Tanzania show that rice fields can prolong the mosquito breeding season well beyond the rainy period, allowing for the continuous presence of larval and adult stages [16-18].

Several factors determine larval productivity in rice fields: water depth, the frequency of drainage and replanting, and the presence of floating aquatic vegetation [19]. Shallow, stagnant areas are associated with high larval density, while increased water flow or partial field drainage can reduce populations [20]. Intermittent irrigation, which involves alternating periods of flooding and drought, has been proposed as a management method to limit permanent habitats while maintaining agricultural yield [21]. Irrigated rice fields can thus transform initially seasonal areas into year-round transmission foci [22].

3.1.2. Gravity-fed irrigation schemes and diversion canals

Gravity-fed irrigation schemes, widely used in arid or semi-arid regions, rely on networks of canals that distribute water from a reservoir or dam to agricultural plots [23]. These infrastructures create linear, often permanent, habitats in the form of canals, ditches, or pools associated with overflows. Mosquito density and persistence in these environments are heavily dependent on hydraulic management, canal cleaning, and bank maintenance [24].

In several African studies, particularly in Niger, Senegal, and Ethiopia, it has been observed that poorly maintained canals favor larval proliferation and help sustain adult populations outside the rainy season [25]. Linear habitats can also promote genetic mixing among local populations, strengthening mosquito resilience to unfavorable conditions and control interventions [26]. Bank landscaping, aquatic vegetation, and localized stagnation areas play a crucial role in larval survival, while agricultural and hydraulic activities can reduce or increase larval productivity depending on their intensity and regularity [27].

3.1.3 Localized irrigation systems

Localized irrigation systems, including drip and localized sprinkler irrigation, are designed to deliver water directly to plant roots, minimizing runoff and field flooding [28]. These systems are often considered less favorable for vector mosquitoes because they reduce the formation of large-scale standing water [29]. However, storage points, reservoirs, tanks, and delivery channels can constitute localized larval refuges, especially if maintenance is insufficient [30].

Studies in East Africa show that localized irrigation generally results in lower larval density compared to rice fields and gravity-fed schemes, but it does not completely eliminate the risks [31]. Mosquitoes often exploit peripheral micro-habitats, shaded areas, and small puddles created by leaks or overflows [32].

3.1.4 Environmental factors modulating the impact of irrigation systems

Beyond the type of irrigation, several environmental and agronomic factors modulate the impact on vector mosquitoes and must be considered [33]. Temperature and humidity play a decisive role: irrigated systems increase relative humidity and stabilize local microclimates, thus creating conditions favorable for adult mosquito survival and the maturation of the *Plasmodium* parasite [34]. This effect is particularly pronounced in semi-arid and arid areas, where water is a limiting factor for the reproduction and persistence of vector populations.

Furthermore, aquatic vegetation contributes significantly to population dynamics. The presence of floating or submerged plants provides a refuge for larvae, protecting them from predators and unfavorable conditions, while vegetated banks offer resting sites for adults and protection against environmental stress [35].

Agricultural practices and fertilization also influence larval habitat productivity. The use of fertilizers promotes the eutrophication of rice fields and canals, stimulating the proliferation of algae and microorganisms that constitute the essential food source for larvae [36]. Similarly, pesticides and other chemical inputs can alter water quality and affect the survival of immature stages, either by reducing natural predatory pressure or by exerting selection for resistant populations [37]. Finally, the infrastructure and maintenance of irrigation systems determine the permanence of larval sites. Canal design, water distribution regulation, and reservoir maintenance condition the existence of standing water points; it is precisely these zones where water persists long-term that present the highest larval densities and contribute most to the seasonal persistence of vector mosquitoes [38].

3.2. Microclimatic and ecological changes induced by irrigation systems

Agricultural irrigation systems modify not only water availability but also local microclimatic and ecological conditions, creating environments favorable for the survival and reproduction of malaria vector mosquitoes [39]. These changes, both direct and indirect, play a decisive role in the seasonal persistence of mosquito populations and the intensity of malaria transmission in irrigated areas (Fig. 1) [40].

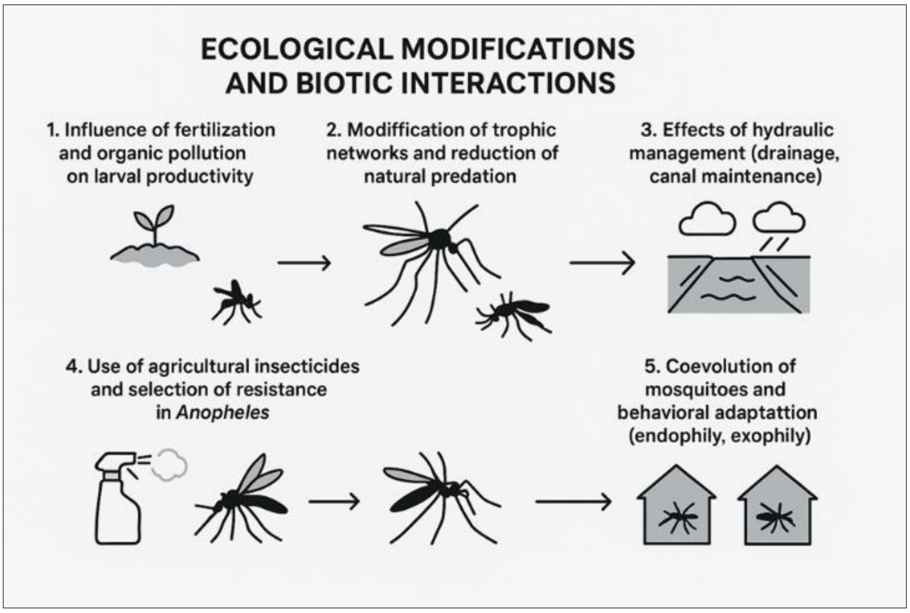

Fig 1: Ecological modifications and biotic interactions affecting mosquito ecology.

3.2.1 Increase in relative humidity

Irrigation helps maintain high levels of relative humidity near fields and hydraulic infrastructure [41]. High humidity is a critical factor for adult mosquito survival, as it reduces dehydration and prolongs their lifespan [42]. Several studies in West and East Africa have shown that irrigated areas maintain relative humidity levels above 70% even during the dry season, whereas non-irrigated areas can drop to 20-30%

during the driest periods [43]. This sustained humidity not only favors adult survival but also the maturation of the *Plasmodium* parasite, accelerating the transmission cycle [44].

3.2.2 Modulation of local temperature

Irrigated systems also influence local temperatures. Standing or slowly flowing water surfaces absorb and release heat differently than dry soil or non-irrigated areas [45]. The overall effect is often a mitigation of thermal extremes: nighttime temperatures remain higher, limiting thermal stress on mosquitoes, while daytime temperatures are slightly modulated [46]. The microclimates thus created favor the survival of larval and adult stages, prolong the lifespan of adults, and improve conditions for parasite development [47].

This thermal regulation is particularly significant in semi-arid areas, where temperatures can become unfavorable for larval development during the dry season [48]. Irrigation thus creates a more stable and favorable environment for vector populations, contributing to off-season persistence [49].

3.2.3 Development of aquatic and riparian vegetation

Irrigation promotes the development of floating, submerged, or emergent aquatic vegetation, as well as dense riparian vegetation along canals and ditches [50]. This vegetation plays a key ecological role in the proliferation of vector mosquitoes [51, 52]. It offers a refuge for larvae, protecting them from predators and temperature variations, while also constituting a nutritional support thanks to the algae and microorganisms that develop there [53]. Adult mosquitoes also use this vegetation cover as a resting site, sheltered from wind, sun, and predators [35]. The importance of this effect varies according to the type of irrigated crop and the level of bank maintenance: flooded rice fields and poorly maintained gravity canals generally exhibit more abundant vegetation, thereby favoring larval survival and increasing adult populations [54].

3.2.4 Creation of humid islands

Irrigated areas often function as "humid islands" in an otherwise dry or semi-arid landscape [55]. These islands maintain conditions favorable for mosquito survival year-round, even outside the rainy season. The presence of these favorable micro-habitats contributes to the spatial and temporal persistence of vector populations, increasing the risk of continuous malaria transmission [56].

In some studies, these humid islands have been identified as local sources of adult mosquitoes, capable of recolonizing peripheral areas when conditions become unfavorable elsewhere [57]. Connectivity between irrigated habitats and non-irrigated areas is a key factor in population dynamics and mosquito resilience to interventions [58].

3.2.5 Modifications of ecological enteractions

Irrigation profoundly transforms the interactions between mosquitoes and ecosystems, influencing biological regulation, host availability, and habitat diversity [59]. The artificial aquatic environments it creates modify predation and competition: depending on the presence of larvivorous fish, invertebrates, or invasive species, the pressure on larvae can decrease or intensify, altering community composition [60]. Simultaneously, the establishment of villages, the development of livestock, and human concentration around irrigated areas increase the proximity between mosquitoes and hosts, strengthening malaria transmission [61]. Finally, the diversity of hydraulic structures and micro-habitats (canals, pools, shaded areas) generates an ecological mosaic favorable to multiple species and larval stages, increasing the biodiversity and complexity of transmission cycles [62]. In summary, irrigation acts as a major ecological factor reorganizing biotic interactions and entomological dynamics in tropical environments [63].

3.3. Entomological trends and seasonal persistence of vector mosquitoes in irrigated areas

The study of malaria vector mosquito populations in African irrigated areas reveals particular entomological trends, marked by a prolonged presence of larvae and adults beyond the rainy season [58, 64]. The seasonal persistence of vectors is modulated by the characteristics of the irrigation systems, associated environmental factors, and interactions with local agricultural practices [65, 66].

3.3.1 Maintenance of off-season abundance

In non-irrigated areas, vector mosquito density generally follows a narrow seasonal pattern: a population peak is observed during the rainy season, when standing water and climatic conditions favor larval development [67]. In contrast, in irrigated areas, numerous studies show that larval and adult densities remain high during the dry season, particularly in rice fields and gravity-fed schemes [68].

For example, studies conducted in East and West Africa have documented persistent larval density in irrigated rice fields, with a larval presence rate exceeding 70% throughout the year, while non-irrigated sites show a drop to less than 10% during the dry season [69-71]. Canals and ditches associated with irrigated schemes also present a notable larval density, maintained by semi-permanent waters, creating survival islands for adult populations.

This continuous presence of adult mosquitoes has a direct impact on the malaria transmission window [72]. In some regions, transmission that was historically seasonal becomes quasi-permanent, with prolonged infection risks for human populations and increased difficulties for public health intervention planning [73].

3.3.2 Specific composition of populations

Irrigation systems influence not only abundance but also the species composition of *Anopheles* populations [74]. Rice fields and calm habitats favor certain species or ecological forms of the *An. gambiae s.s.* complex, while other species, such as *An. arabiensis*, can thrive in the linear habitats of canals [75].

Studies in West Africa have shown that the relative proportion of *An. funestus* increases in irrigated rice field areas with dense aquatic vegetation, due to this species' preference for semi-permanent habitats with cover vegetation [76]. The dynamics of *Anopheles* species are also influenced by the micro-habitats created around reservoirs and gravity canals, which can favor exophilic or exophagic species, modifying feeding and resting behaviors [77].

3.3.3 Development cycles and phenology

Mosquito phenology is directly affected by the permanent or prolonged availability of larval habitats [78]. Rice fields, ditches, and semi-permanent pools allow for several reproductive cycles per year, even during the dry season [79].

Larvae find favorable conditions in terms of temperature, humidity, and microbial food availability, which reduces the usual seasonal constraints (Fig. 2) [80].

This continuous proliferation leads to sustained larval recruitment, allowing for the maintenance of a stable, or even growing, adult population [81]. Entomological models suggest that irrigated areas can increase the average number of mosquito generations per year, which has direct implications for malaria transmission, as each generation represents an additional opportunity for the maturation of the *Plasmodium* parasite [81].

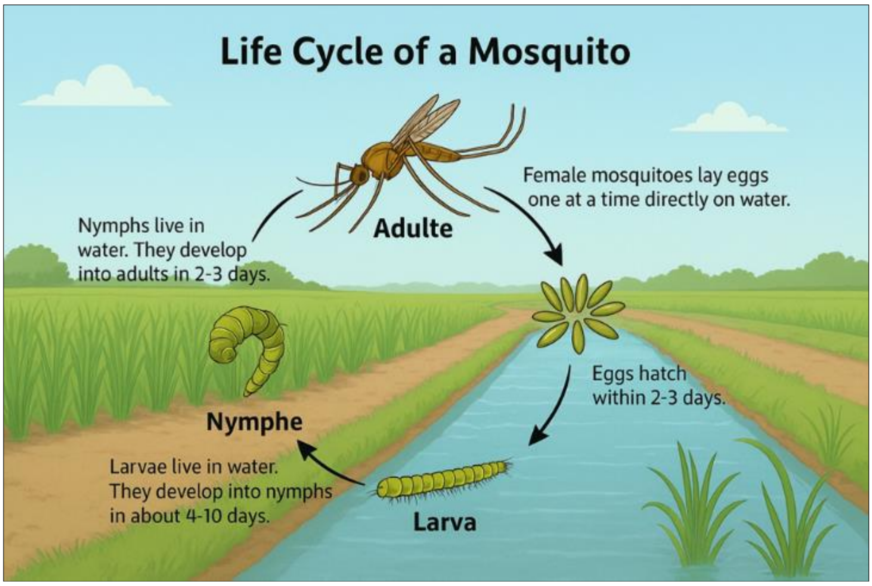

Fig 2: Life Cycle of Mosquitoes in Irrigated Agricultural Environments

3.3.4 Effects of insecticide resistance

Irrigated agricultural areas often expose mosquitoes to agricultural insecticides, particularly organophosphates, pyrethroids, and carbamates [82]. This exposure can lead to the selection for resistant populations, reducing the efficacy of classic interventions such as Long-Lasting Insecticidal Nets (LLINs) and Indoor Residual Spraying (IRS) [83]. The persistence of resistant populations contributes to maintaining a high level of vector density and prolonging seasonal transmission [84].

Studies in Burkina Faso and Niger have documented *An. gambiae s.l.* populations with high rates of pyrethroid resistance in irrigated areas, particularly around rice fields and poorly maintained canals, reinforcing the role of irrigation systems in the dynamics of mosquito persistence [85, 86].

3.4. Mitigation measures and management strategies

Water management is an essential lever for limiting mosquito proliferation in irrigated schemes [87]. Intermittent irrigation, alternating flooding and drying, reduces larval survival in rice fields while maintaining agricultural yield, by limiting the formation of permanent habitats favorable to *Anopheles* larvae [88]. Regular cleaning of canals and ditches, as well as the adapted design of infrastructure with drainage and managed banks, also helps limit aquatic micro-habitats [89].

Biocontrol complements these measures, notably through the introduction of natural predators, such as larvivorous fish and certain predatory insects, or through the application of biological larvicides such as *Bacillus thuringiensis israelensis* and *Bacillus sphaericus*, targeting larvae without significantly affecting other organisms [90]. These strategies fit within an Integrated Vector Management (IVM) approach, particularly suited to areas where excessive use of chemical insecticides has led to the emergence of resistance [91, 92].

Agricultural practices also influence mosquito population dynamics. Crop rotation, planting schedules, and the management of aquatic vegetation help reduce larval habitats [93], while the reasoned reduction of insecticide use prevents the selection of resistant mosquitoes [94].

Entomological surveillance, including larval and adult monitoring as well as insecticide resistance analysis, allows for the adjustment of interventions and the targeting of at-risk areas using predictive models [95]. Coordination between agriculture, public health, and the environment strengthens the effectiveness and sustainability of the measures [96].

Finally, the involvement of local communities is essential. Education on the reduction of domestic larval habitats, the promotion of bed nets, and participation in infrastructure maintenance contribute to limiting mosquito reproduction and strengthening the success of integrated control strategies [97].

4. Conclusions

This synthesis clearly demonstrates that irrigation systems, while vital for agricultural intensification and food security in sub-Saharan Africa, are also major ecological drivers of malaria vector persistence. By modifying hydrological regimes, microclimatic conditions, and trophic networks, irrigated agroecosystems create continuous breeding opportunities for *Anopheles* mosquitoes, thereby extending transmission beyond the rainy season. Hydrological stabilization, habitat diversification, predator reduction, and agrochemical selection act synergistically to sustain vector populations during dry periods, progressively transforming formerly seasonal malaria zones into perennial or semi-perennial transmission areas.

Consequently, irrigation planning and management must systematically integrate health and environmental risk assessments at all stages, from design and construction to operation and maintenance. Health-oriented hydrological designs that promote adequate drainage, controlled water-level fluctuations, and intermittent irrigation should be prioritized. Environmental and Health Impact Assessments

(EHIA) must identify potential breeding sites and propose mitigation measures, supported by remote sensing and GIS tools for spatial monitoring of water bodies and mosquito habitats.

The convergence between water management and vector ecology calls for an Integrated Vector and Water Management (IVWM) approach, combining hydraulic efficiency with vector control. Practices such as periodic field drying, proper drainage maintenance, vegetation clearance, and continuous water flow can effectively limit larval habitats. Likewise, Integrated Pest and Vector Management (IPVM) should align agricultural pesticide use with public health vector control programs, promoting bio-rational alternatives and farmer training to reduce contamination and delay insecticide resistance.

Sustainable malaria control in irrigated environments requires cross-sectoral collaboration among agriculture, health, water, and environmental authorities, supported by research institutions through long-term ecological and epidemiological studies. Adopting a *One Health* framework is crucial, ensuring irrigation projects enhance not only agricultural productivity but also ecological integrity and public health safety. Through this integrated, eco-health-based governance, irrigation can evolve from a malaria amplifier into a vector-mitigating engine of sustainable rural development.

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