species-specificity constraints, and logistical challenges in large-scale deployment (Figure 2) (Benelli et al., 2016; Dahmana and Mediannikov, 2020). Integrating biological controls with environmental management within an integrated vector management framework can enhance overall effectiveness but requires careful evaluation of ecological impacts and operational feasibility (Hamed et al., 2022).

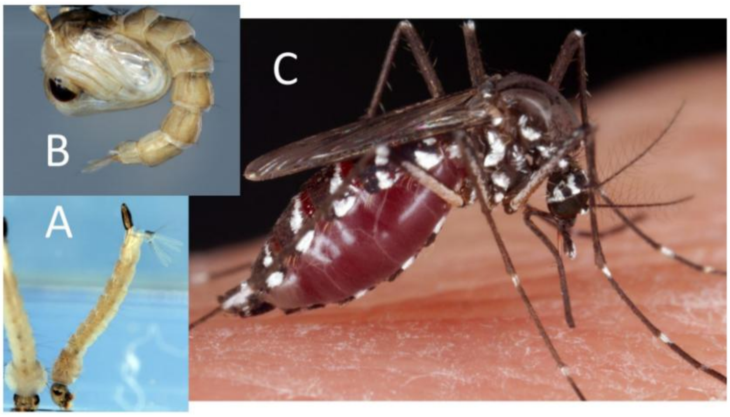

Figure 2 *Aedes albopictus* strain: (A) larvae, (B) pupa, and (C) adult (Adopted from Benelli et al., 2016)

4.3 Insecticide resistance and behavioral adaptations

The rapid evolution of insecticide resistance in mosquito populations poses a major threat to the continued success of chemical-based interventions. Resistance mechanisms include metabolic detoxification, target site mutations, and cuticular changes that reduce insecticide penetration or binding. Importantly, standard laboratory assays often fail to predict the practical impact of resistance on field efficacy due to differences in mosquito age, behavior, and environmental exposure (Namias et al., 2021). This discordance complicates resistance monitoring and necessitates improved guidelines that reflect real-world conditions for better programmatic decision-making.

Beyond physiological resistance, mosquitoes exhibit behavioral adaptations such as altered feeding times, increased outdoor biting, or avoidance of treated surfaces that reduce contact with insecticides. These plastic or constitutive behavioral changes undermine indoor interventions like IRS and ITNs by enabling vectors to evade lethal exposure (Benelli and Beier, 2017; Carrasco et al., 2019). Addressing both physiological resistance and behavioral shifts requires diversified control strategies incorporating novel tools alongside existing methods to sustain malaria transmission reduction efforts effectively (Figure 3) (Benelli and Beier, 2017; Carrasco et al., 2019).

5 Novel and Alternative Mosquito Control Technologies

5.1 Plant-based insecticides and natural product applications

Plant-based insecticides have emerged as promising eco-friendly alternatives to synthetic chemicals for mosquito control. These natural products, derived from various plant extracts and essential oils, exhibit larvicidal, adulticidal, and repellent properties that target multiple mosquito life stages. Their complex chemical compositions reduce the likelihood of resistance development in mosquito populations, making them valuable tools in integrated vector management. For example, neem oil contains bioactive compounds such as azadirachtin that disrupt mosquito development and behavior, demonstrating efficacy as ovicides, larvicides, and repellents while being environmentally safe (Chatterjee et al., 2023; Hillary et al., 2024).

Advances in green nanotechnology have further enhanced the potential of plant-based insecticides by enabling the synthesis of metallic nanoparticles using plant extracts. These nanoparticles exhibit broad-spectrum mosquitocidal activity with improved stability and targeted delivery compared to conventional formulations. Such green-synthesized nanoparticles offer biodegradable, non-toxic options that minimize environmental impact and can be tailored for specific vector species. However, challenges remain in scaling up production and ensuring consistent field efficacy under diverse ecological conditions (Kumar et al., 2020; Onen et al., 2023).