Laboratory Evidence of the effect of Water Availability on *Aedes* Mosquito Population Dynamics: A Scoping Review

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Abstract

The increasing geographical spread, abundance and activity of invasive *Aedes* mosquitoes are cause of concern for public health at local and global scales. These species transmit diseases such as dengue, Chikungunya, Yellow Fever, and Zika, which can cause outbreaks in endemic and non-endemic settings. Unlike temperature, whose impact on key entomological traits has been extensively studied, the impact of water availability on *Aedes* traits and hence population dynamics has been largely overlooked. This scoping review aims to fill this gap by compiling the published laboratory evidence of the effect of precipitation and water availability on the bionomics of invasive *Aedes* species (including *Ae. albopictus, Ae. aegypti, Ae. japonicus,* and *Ae. koreicus*). We found eleven studies investigating the effect of water availability on the bionomics of invasive *Aedes* mosquitoes, none of which were conducted with *Ae. japonicus* or *Ae. koreicus*. The effect of rainfall intensity and duration on the survival and development of *Ae. albopictus* and *Ae. aegypti* was investigated by three studies, which showed that heavy and long-lasting precipitation leads to higher immature mortality in both species. The impact of water availability on the survival to adulthood, development, and oviposition behaviour of *Ae. albopictus* and *Ae. aegypti* was explored by seven studies. The studies reported higher survival and faster development in water volumes below 2 litres, and that the amount of water contained can favour oviposition, with females laying significantly less eggs in containers that are full compared to those that are half full. An additional two studies explored the relationship between evaporation and adult survival and body size of *Ae. albopictus* and *Ae. aegypti*. Evaporation was found to have a detrimental effect on the survival and egg hatching of *Ae. albopictus,* but not of *Ae. aegypti*. Interestingly, *Ae. albopictus* was also found to have bigger body sizes when exposed to evaporation. This review provides a summary of the experimental evidence currently published on the effect of water availability on invasive *Aedes* traits, and highlights how key research questions and knowledge gaps still remain. These should be addressed by future experiments to be able to generate data-driven predictions of the geographical expansion

of these species under changing rainfall patterns, and the potential impact of containment strategies.

Keywords: *Aedes albopictus*, review, rainfall, traits

Introduction

Aedes Invasive Mosquitoes (AIMs), like *Ae. aegypti, Ae. albopictus, Ae. japonicus*, and *Ae. koreicus,* are vectors of several diseases of great concern globally, as there is evidence that their invasion and establishment is closely linked with the local transmission of arboviruses, including dengue, chikungunya and Zika viruses (ECDC, 2016, 2023; Farooq et al.; Farooq et al., 2025). At a global level, the number of arbovirus cases has been constantly increasing over the past decades. For instance, the number of reported dengue cases globally has increased from half a million in 2000 (WHO, 2024) to a record 14 million cases in 2024 (ECDC, 2025a). In Europe, dengue and chikungunya outbreaks have more frequently been reported in Italy, France, and Spain (ECDC, 2025b, 2025c), demonstrating the increasing public health relevance and concern posed by dengue and other *Aedes*-borne infections in non-endemic settings.

Originally from Africa and East Asia, AIMs are now present in the Americas, Oceania, and Europe (ECDC, 2014a, 2014b, 2016, 2023). Their geographical range, and that of arboviral infections, is mainly driven by climatic conditions (San Miguel et al., 2024). As ectothermic organisms (VDCI, 2024), temperature determines survival and regulates the life-history traits of AIMs, which has been studied extensively in the literature (Da Re et al., 2025; Johnson et al., 2015; Mordecai et al., 2017). Another important climatic variable shaping mosquito population dynamics is rainfall, as water is essential for the aquatic stages on their lifecycle (Figure S1). Typically, AIM species lay eggs above the surface of the water in containers, so rainfall leads to the creation of outdoor breeding sites, including rock pools, flower pots, and tyres (Herath et al., 2024). Eggs then require immersion to hatch; thus, rainfall or other water sources are needed to trigger egg hatching. Rainfall also contributes to refilling outdoor breeding sites, thus allowing the continuous development of larvae and pupae, which are the aquatic stages of the mosquito life cycle (Figure S1). From a population dynamics perspective, *Aedes* abundance has been observed to vary in response to seasonal changes, with *Ae. aegypti* being more abundant in the dry season and the beginning of the wet season but *Ae. albopictus* dominating later in the wet season (Marina et al., 2021; Reiskind & Lounibos, 2013).

Despite the importance of rainfall for the proliferation of mosquitoes, the complex and sometimes counter-intuitive effect that it has on AIMs abundance has not been well characterised to date. It has been hypothesised that there is an optimal range of rainfall that promotes mosquito abundance, below which abundance may decrease due to lack of rain and above which there could be a negative effect on mosquito population due to the flushing of larvae from their breeding sites (Caldwell et al., 2021; Liu et al., 2025; Padmanabha et al., 2010; White et al., 2025). On the other hand, it has been observed that arboviral outbreaks often follow and correlate with floods with some lag, and it has been hypothesised that rainfall ultimately always leads to an increase in mosquito abundance due to providing additional breeding sites and triggering egg hatching (Acosta-España et al., 2024; Roiz et al., 2015). To date, it is unclear how water availability and rainfall affect *Aedes* life history traits and ultimately population dynamics, especially from a quantitative perspective which could be used to parameterise mathematical models of *Aedes*-borne infections.

This study aims to systematically collect and collate from published studies the existing laboratory evidence quantifying the relationship between water availability and life history traits of the main invasive mosquito species in Europe, namely *Ae. albopictus*, *Ae. aegypti, Ae. japonicus,* and *Ae. koreicus*. The data collated in this work can help identify open knowledge gaps and better quantify how the current and future climate will affect the risk of *Aedes*-borne disease outbreaks in both endemic and at-risk settings.

Methods

Search strategy

This scoping review follows the guidelines of the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) chart (Figure S2).

All studies were extracted from Embase, Web of Science, and Scopus databases and imported into Endnote 20 and Covidence. A comprehensive term search was performed to ensure that no studies were missed, consisting of the following terms and their synonyms: [(*Aedes aegypti*) OR (*Aedes albopictus*) OR (*Aedes japonicus*) OR (*Aedes koreicus*)] AND [(Precipitation)] (Table S1). We only included studies containing one of the species names given in Table S1 in combination with a rainfall related keyword in the abstract or title. There were no time, language or location restrictions. The search was conducted on the 6th of November 2025 and studies published after this date were not included.

Study selection

Study selection was performed by screening titles and abstracts to ensure eligibility. Three reviewers (EIK, DDR, GM) performed the initial screening of the articles, and each study was reviewed by two different reviewers. A fourth reviewer (ID) settled any discrepancies between the three reviewers during screening. A single reviewer (EIK) performed the full-text review and the data extraction.

Eligibility criteria

The studies had to meet five inclusion criteria to be selected: i) they had to be published in a peer-reviewed journal; ii) studies had to present primary data from laboratory or field experiments; iii) the outcome of the studies was one or more life history traits, such as survival, developmental time, or body size; iv) the water availability-related variable tested had to be quantifiable, in terms of precipitation intensity or duration, stagnant water volume, or water evaporation (and synonyms); v) the species investigated were one or more of the following: *Ae. aegypti, Ae. albopictus, Ae. japonicus,* or *Ae. koreicus*.

Data extraction and analysis

The data were extracted from all eligible studies and collated in Excel following VectorByte standards (Johnson et al., 2025), using the online tool Automeris (Rohatgi, 2024) to determine the values reported in figures. The following information was recorded: the type of water availability tested, the outcome measured, the location of the study, the source of the mosquito line used in the study (laboratory or field), the ambient temperature, the life stage during the experiment, and the food regimen. Data analysis was carried out in R version 4.3.3.

Results

Identification of studies

We obtained a total of 11,495 articles from Embase, Web of Science, and Scopus, of which 5,777 were duplicates (Figure 1). After abstract selection of the remaining 5,718, we had 54 eligible studies according to the inclusion criteria. One study was not available in full text and was therefore excluded from the review (Chen, 1951). After full-text review, 11 studies were included for analysis (Alto & Juliano, 2001; Costanzo et al., 2005; de Brito & Paulo Forattini, 2004; Dieng et al., 2012; Keirans & Fay, 1970; Koenraadt & Harrington, 2008; Lushasi et al., 2025; Medici et al., 2011; Parker et al., 2019; Richardson et al., 2013; Sudia, 1952). A summary of the studies screened and selected in this review is described in Figure 1.

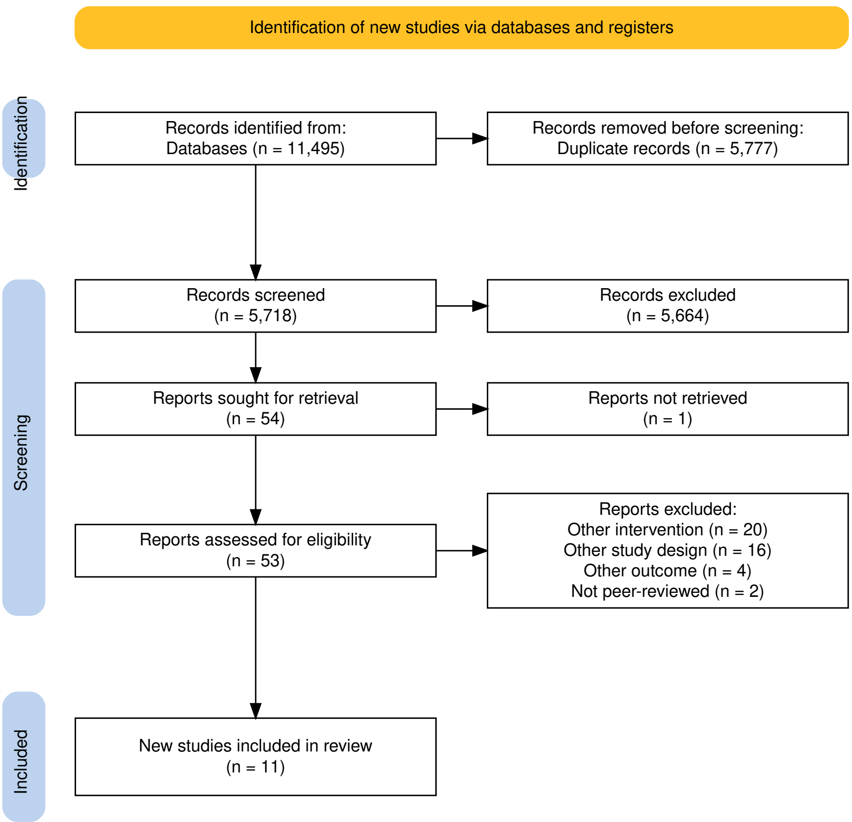

Figure 1: PRISMA flow diagram for the search of laboratory evidence on the relationship between precipitation and *Aedes* species. Created with R package PRISMA2020.

Characteristics of included studies

The selected studies consisted of laboratory experiments directly measuring the impact of rainfall, water evaporation, or water volume on *Ae. aegypti* and *Ae. albopictus* life history traits. No studies reporting trait variations as a function of water availability were found for *Ae. japonicus* and *Ae. koreicus*. Overall, five studies used *Ae. aegypti* (Keirans & Fay, 1970; Koenraadt & Harrington, 2008; Lushasi et al., 2025; Richardson et al., 2013; Sudia, 1952) and four used *Ae. albopictus* (Alto & Juliano, 2001; de Brito & Paulo Forattini, 2004; Dieng et al., 2012; Medici et al., 2011), whilst two papers studied both species (Costanzo et al., 2005; Parker et al., 2019). Six studies were conducted in the Americas, and four in the USA (Alto & Juliano, 2001; Costanzo et al., 2005; Parker et al., 2019; Sudia, 1952), one in Puerto Rico (Keirans & Fay, 1970), and one in Brazil (de Brito & Paulo Forattini, 2004). In Asia, one study was conducted in Malaysia (Dieng et al., 2012) and another in Thailand (Koenraadt & Harrington, 2008). The remaining three studies were conducted in Australia (Richardson et al., 2013), Italy (Medici et al., 2011), and Tanzania (Lushasi et al., 2025).

Most of the selected studies evaluated different aspects of water availability or rainfall and measured their impact on different life history traits of *Ae. aegypti* and *Ae. albopictus*. Two studies investigated the impact of rainfall intensity and duration on the survival of larvae and pupae, which was assessed by determining how many individuals remained in the breeding site and how many were flushed out using simulated rain for *Ae. albopictus* (Dieng et al., 2012) and *Ae. aegypti* (Koenraadt & Harrington, 2008) mosquitoes. Rather than simulating rain falling from a certain height, Sudia (1952) simulated different current speeds to assess the impact of water intensity on the survival of *Ae. aegypti* larvae whilst swimming.

Some studies assessed the impact of water availability on different *Aedes* traits. Four studies quantified the effect of available water volume in the breeding site on the number of *Ae. albopictus* larvae and pupae produced (de Brito & Paulo Forattini, 2004; Medici et al., 2011; Parker et al., 2019), larval development time (Richardson et al., 2013) or pupation rate (Medici et al., 2011). The study by Parker et al. (2019) also included *Ae. aegypti* specimens as well as *Ae. albopictus*. Lushasi et al. (2025) also evaluated the impact of water availability on traits such as survival, larval development time, and wing size, but using *Ae. aegypti* specimens. The study by Dieng et al. (2012) also reported the number of eggs laid in response to different water levels.

Finally, two studies quantified the effect of water evaporation on *Aedes* traits (Alto & Juliano, 2001; Costanzo et al., 2005). The survival of eggs, larvae, and adults when exposed to water evaporation was explored for *Ae. albopictus* alone (Alto & Juliano, 2001), or in combination with *Ae. aegypti* (Costanzo et al., 2005). The study by Alto and Juliano (2001) also measured the variation in development time, and body size on eggs, larvae, and adults in response to evaporation. These results are summarised in Table *1*.

Heavier rainfall causes higher larval mortality

The effect of rainfall duration on larval survival was measured in two studies, for *Ae. albopictus* (Dieng et al., 2012) and *Ae. aegypti* (Koenraadt & Harrington, 2008). In laboratory setting, they exposed containers with *Ae. albopictus* or *Ae. aegypti* larvae and pupae to different regimes of simulated rain falling from a distance of either 2.9 (Koenraadt & Harrington, 2008) or 10 meters (Dieng et al., 2012). The containers were allowed to fill up and overflow, and the authors counted the number of remaining larvae in the containers. Since the immature mosquito stages are purely aquatic, those that were expelled from the containers during the experiment were counted as dead. The authors in both studies compared the treatments by Analysis of Variance (ANOVA).

For *Ae. albopictus,* the low rainfall treatment consisted of exposing larvae and pupae to short (10 min) and light precipitation (6 mm in total), whilst precipitation in the high rainfall treatment was long (25 min) and heavy (62 mm in total). Both treatments were tested in small (60 ml) and large (300 ml) containers. Low rainfall only induced 0-10% larval and pupal mortality (Figure *2*A), and the authors found no statistically significant differences in mortality between those in small and large containers when they conducted an ANOVA ($F = 2.25$, $p = 0.151$). However, high rainfall caused 12-76% *Ae. albopictus* mortality (Figure *2*A), which was significantly higher than the mortality caused by low rainfall for larvae ($F = 8.03$, $p = 0.011$) and pupae ($F = 14.44$, $p = 0.001$). They also reported that high rainfall caused significantly higher larval ($F = 49.63$, $p < 0.001$) and pupal ($F = 11.02$, $p = 0.004$) mortality in small containers compared to large ones. Therefore, longer and heavier rainfall was detrimental to the survival of *Ae. albopictus* larvae and pupae, but due to the experimental design, it is not possible to disentangle whether it was the duration of rainfall or the flow intensity that led to higher mortality.

Conversely, *Ae. aegypti* survival was measured when containers were exposed to different periods of time (0, 15, 25, 60 min) of a constant water flow (0.88 mm/min) at different water temperatures (16, 24, 25 ˚C) (Figure *2*B). Rainfall exposure time had no significant effect on larval and pupal survival (ANOVA: $F = 0.311$, $p = 0.733$). Moreover, water temperature had no significant effect on the survival of *Ae. aegypti* larvae and pupae ($F = 2.958$, $p = 0.088$). Additionally, the study by Koenraadt and Harrington (2008) found that rainfall duration did not affect the time to pupation of *Ae. aegypti* larvae (Figure S2).

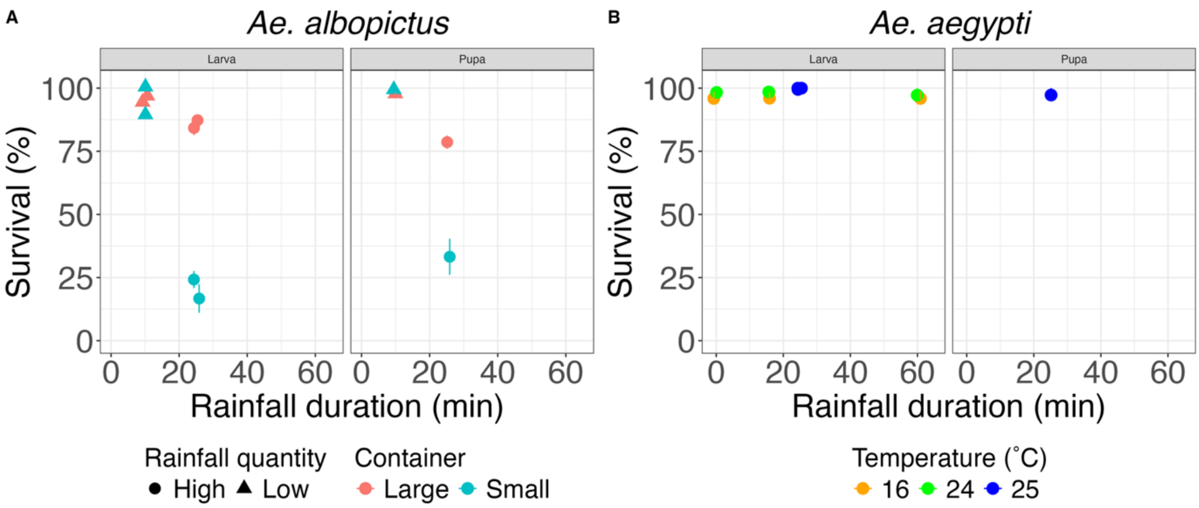

Figure 2: Impact of different durations of precipitation on the survival of *Aedes* species. (A) Mean survival percentage of *Ae. albopictus* larvae and pupae in response to a low rainfall scenario (10 min of 6 mm of total rainfall, triangle) and a high rainfall scenario (25 min of 62 mm of total rainfall, circle) with standard error (errorbars). Both treatments were tested in small (blue) and large (red) containers. Data from Dieng et al. (2012). (B) Mean survival percentage (point) and 95% confidence intervals (errorbar) of *Ae. aegypti*

larvae and pupae in response to 0, 15, 25, and 60 min of rainfall at the same (0.88 mm/min) intensity with water temperature of 16˚C (orange), 24˚C (green), and 25˚C (blue). Data from Koenraadt and Harrington (2008).

Unlike these experiments, which simulated the ability of larvae and pupae to remain in the breeding site in response to rainfall, Sudia (1952) simulated the effect of water current speed on the survival of *Ae. aegypti* larvae by assessing whether they were able to reach the adult stage after swimming in the water current for a given period of time. These larvae were placed in a "stream-tank" and had to swim against a given current speed, which varied between 0.5 to 4 feet/second (equivalent to 0.5 to 4.4 km/h) for different durations of time (4 to 72 hours). For a given current speed, they found that larval mortality was significantly different for the extremes times of exposure to flowing water, longer exposure inducing significantly higher mortality than shorter exposure to the water current (Sudia, 1952). For instance, when the speed of current was 0.5 ft/s (0.5 km/h), 78% (95% CI: 64-89%) of larvae survived when swimming for 8 hours compared to only 22% (95% CI: 11-36%) when swimming for 72 hours (Figure *3*). Moreover, the authors found that for a given duration of exposure, larval mortality was significantly higher at the extreme current speeds (Sudia, 1952). For instance, when larvae had to swim against the current for 8 hours, 78% (95% CI: 64-89%) of larvae survived when exposed to a light current (0.5 ft/s or km/h) compared to no survivors when exposed to stronger currents (3 to 4 ft/s or 3.3 to 4.4 km/h). These results suggest that both the duration of exposure and the speed of flowing water impact *Ae. aegypti* larval survival. These findings are in contrast with the previous results by Koenraadt and Harrington (2008), which found that up to an hour of rainfall did not affect larval survival. However, the shortest experiment in Sudia (1952) was four hours long, suggesting that *Ae. aegypti* larvae may only be affected by rainfall after several hours.

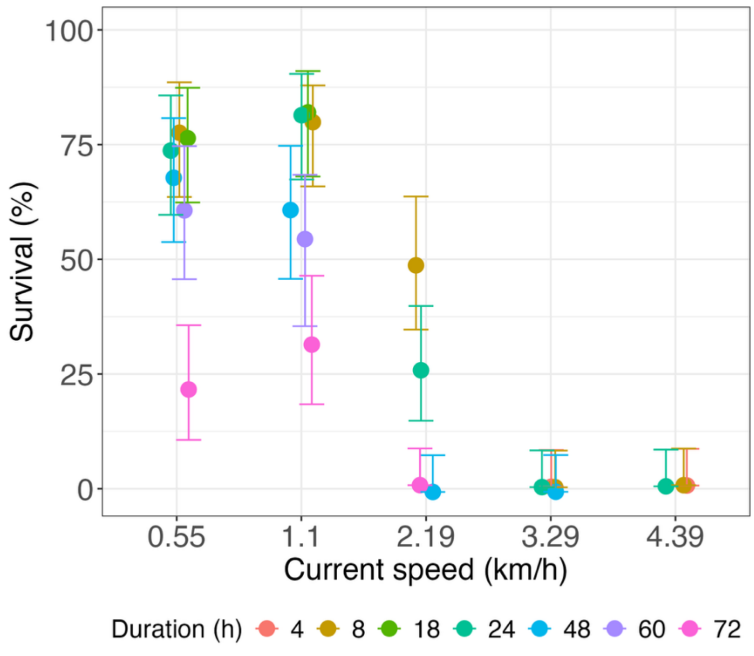

Figure 3: Impact of water speed on the survival of *Ae. aegypti* larvae to adulthood. Mean survival percentage of *Ae. aegypti* larvae exposed to current speeds (0.5, 1, 2, 3, and 4

ft/s) in a stream-tank is represented with the 95% confidence interval bars. Experiments were run for 4 h (red), 8 h (brown), 18 h (green), 24 h (aquamarine), 48 h (blue), 60 h (purple), and 72 h (pink) before the larvae were retrieved and bred to adulthood to measure survival. Data from Sudia (1952).

Survival, development, and oviposition are negatively affected by higher water availability

The impact of water availability on different *Aedes* life history traits was measured in laboratory conditions by placing larvae in different volumes of water (0.2, 0.5, 1, 2, 2.5, 10 L) and measuring different life history traits, including survival to adulthood, developmental time, and number of eggs laid. The experiments were performed using *Ae. albopictus* (Medici et al., 2011), *Ae. aegypti* (Lushasi et al., 2025), and both species (Parker et al., 2019).

Water availability had different effects on survival to adulthood on the two species depending on food availability. For *Ae. albopictus,* the number of adults emerging was lower in higher volumes of water than in lower volumes regardless of food availability. When bred in 0.2 L and 10 L, the adult emergence of *Ae. albopictus* decreased from 34% (95% CI: 31-36%) to 20% (95% CI: 18-22%) and from 56% (95% CI: 54-59%) to 45% (95% CI: 42-47%) at low and high food treatments, respectively (Figure *4*A). For *Ae. aegypti*, survival to adulthood also decreased by 28% when reared in 10 L compared to 0.2 L of water at low food density (Figure *4*B). However, when large amounts of food were given, the emergence of *Ae. aegypti* adults increased from 43% (95% CI: 40-45%) in 0.2 L to 54% (95% CI: 51-56%) in 10 L (Figure *4*B). Therefore, increasing volumes of water seem to be detrimental for the survival of both species, but this does not apply to *Ae. aegypti* when there is no competition for food.

Additionally, larval development was slower (i.e. the development time was longer) in larger volumes of water of up to 10 L for both species (Figure S3). However, an opposite trend was observed for *Ae. aegypti* in containers of up to 100 L (Figure S3). Male pupation rate of *Ae. albopictus* was found to be slower in increasing volumes of water (Figure S4). Interestingly, Lushasi et al. (2025) found that adult *Ae. aegypti* were significantly larger when larvae were bred in 1 L of water compared to 0.5 L ($p < 0.001$). Therefore, higher water availability up to modest volumes may slow down the development of both species and lead to bigger adults emerging.

Water availability was also shown to affect the reproductive behaviour of female *Ae. albopictus*, which was evaluated by Dieng et al. (2012). Females laid on average 47 eggs in oviposition cups that were half full, compared to less than 15 eggs in cups that were full, which they reported as significant ($F = 16.88$, $p < 0.05$). Water availability also regulates egg hatching, as Keirans and Fay (1970) showed that the hatching success of *Ae. aegypti* peaked when eggs were submerged for 3 days (Figure S6).

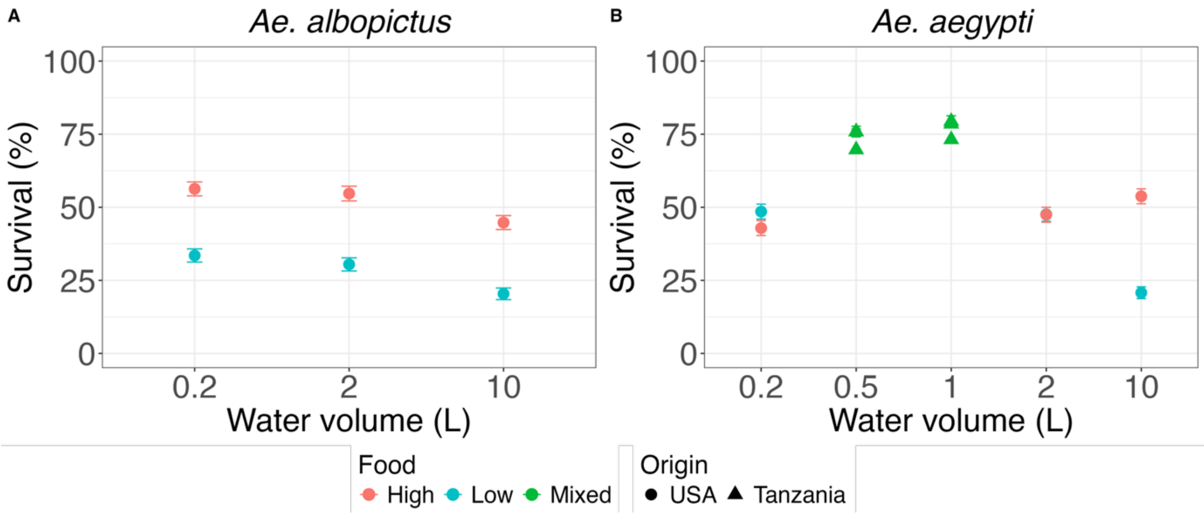

Figure 4: Effect of volume of breeding water available on the survival of *Aedes* species from larvae to adulthood. Mean survival percentage of larvae that reached adulthood when bred in fixed amounts of water (0.2, 2, 2.5, 10 L) is shown with the standard error (errorbars) for (A) *Ae. albopictus* and (B) *Ae. aegypti*. The larvae were given low (blue), high (red) and mixed (green) levels of food during development. Mixed levels of food refer to the results obtained from averaging the observations obtained with high amounts of food and no food. Data from Parker et al. (2019) and Lushasi et al. (2025).

Water evaporation decreases the survival of *Ae. albopictus* but not *Ae. aegypti*

Two studies quantified the effect of exposing mosquito eggs to partial or full water evaporation on the total number of *Ae. albopictus* and *Ae. aegypti* larvae and adults produced at the end of the experiment (Alto & Juliano, 2001; Costanzo et al., 2005). The study by Costanzo et al. (2005) started with 60 *Ae. albopictus* or *Ae. aegypti* larvae in cups that were left to evaporate to 50% or 100% of their total volume (160 mL). In the latter case, the cups were dry for two weeks before being refilled. The experiment by Alto and Juliano (2001) only consisted of *Ae. albopictus* specimens and started with 100 larvae that were exposed to 10, 75, and 100% evaporation, and the cups (120 mL) with full evaporation remained dry for five days before being refilled. The authors then counted the number of live larvae or adults after 120 (Costanzo et al., 2005) and 105 (Alto & Juliano, 2001) days of experiment (Figure 5A).

For *Ae. albopictus*, Costanzo et al. (2005) reported that full evaporation significantly decreased the mean number of adults (ANOVA: $F = 21.25$; $p < 0.001$) and larvae ($F = 7.12$; $p = 0.0184$) compared to 50% evaporation. In line with these findings, Alto and Juliano (2001) showed that fewer adults emerged in the treatment with full evaporation compared to 25% and 90% evaporation, especially at 30˚C and 26˚C. However, evaporation had no significant effect on adult emergence when the experiments were carried out at 22˚C (Alto & Juliano, 2001).

For *Ae. aegypti*, Costanzo et al. (2005) found that water evaporation seemed to have a negative effect on the number of *Ae. aegypti* at the end of the experiment, but this effect was not significant for both larvae (F = 0.83; p = 0.3732) and adults (F = 1.91; p = 0.18220) (Figure 5B). Their findings also indicate that higher levels of water evaporation decrease egg hatching for *Ae. albopictus*, but not for *Ae. aegypti* (Figure S6). Therefore, we found evidence that water evaporation may negatively impact survival of different life stages of *Ae. albopictus,* but not necessarily for *Ae. aegypti*.

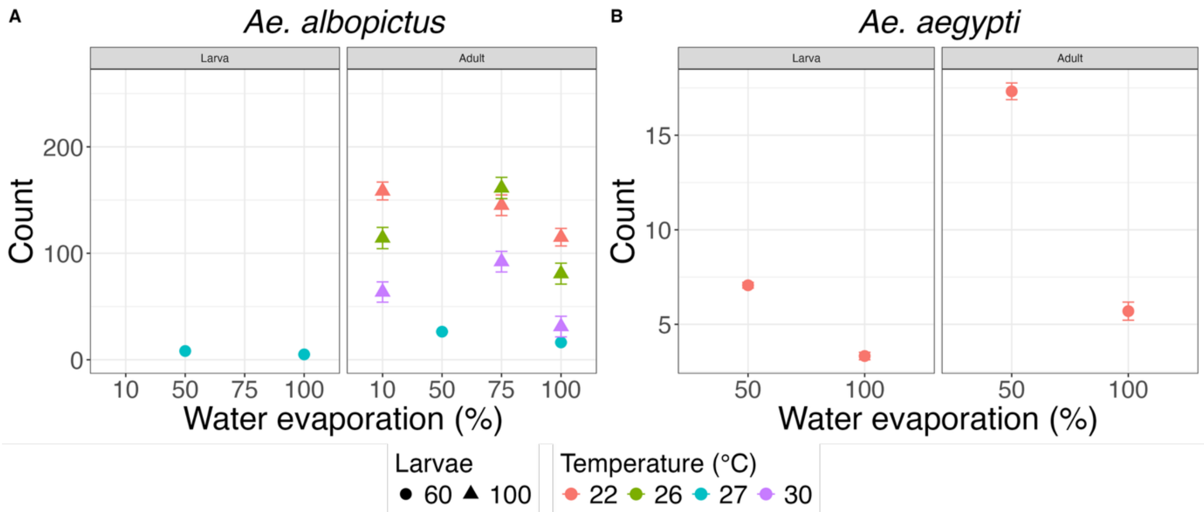

Figure 5: Effect of water evaporation on the number of *Aedes* larvae and adult mosquitoes present after several generations. (A) Mean number of *Ae. albopictus* adult and larvae that were present at the end of the experiments when 10, 50, 75, or 100% of the water evaporated before being refilled, shown with the standard error bars (errorbar) to account for replicates. The experiments were run at an air temperature of 22˚C (red), 26˚C (khaki), 27˚C (green), and 30˚C (blue). The data points come from two studies, one in Florida that lasted 120 days (Costanzo et al., 2005) and one in St Louis in the US that lasted 105 days (Alto & Juliano, 2001). (B) Mean number of *Ae. aegypti* adult and larvae that emerged at the end of the experiments when 50 or 100% of the water evaporated before being refilled is shown with the standard error bars (errorbar). The study reported that full evaporation had no significant effect on the number of *Ae. aegypti* adults or larvae compared to 50% evaporation (F = 0.83; p = 0.3732). Data from Costanzo et al. (2005).

Water evaporation leads to bigger *Ae. albopictus* adults

The effect of water evaporation on the size of *Ae. albopictus* was examined by Alto and Juliano (2001) who found that higher levels of evaporation lead to bigger wing sizes in *Ae. albopictus* adults. When 10% of the water volume evaporated, the size of the wing was around 2.06 mm, which was not significantly different from the 2.1 mm wing size under the 75% evaporation treatment. However, the 2.13 mm wings obtained at 100% water evaporation were significantly larger than those obtained at 10% water evaporation as shown by the reported bivariate pairwise contrasts (Alto & Juliano, 2001).

Table 1: Summary of the effect of precipitation, water availability and evaporation on *Aedes* traits. (*): the experiment by Dieng et al. (2012) consisted of light (short and light rain) vs high (long and hard) rainfall treatments, making it challenging to disentangle the individual effect of rainfall intensity and duration on *Ae. albopictus* survival.

Intervention	**Life history trait**	***Ae. albopictus***	***Ae. aegypti***
Rainfall intensity	Survival (larvae/pupae)	Decreases at higher intensity* (Dieng et al., 2012)	Decreases when swimming in stronger currents (up to 4.4 km/h) (Sudia, 1952)
Rainfall duration	Survival (larvae/pupae)	Decreases after 25 min* (Dieng et al., 2012)	Decreases after 4 h (Koenraadt & Harrington, 2008; Sudia, 1952)
	Egg-pupa development time	-	No effect (Koenraadt & Harrington, 2008).
Water availability	Survival to adulthood	Decreases in volumes above 2 L (de Brito & Paulo Forattini, 2004; Parker et al., 2019)	Decreases in volumes above 2 L at low food density (Parker et al., 2019)
	Egg-adult development time	Slower in containers with more than 2 L (Medici et al., 2011; Parker et al., 2019)	Slower in containers with more than 2 L (Lushasi et al., 2025; Parker et al., 2019; Richardson et al., 2013)
	Male pupation rate	Decrease in volumes above 1.5 L (Medici et al., 2011)	-
	Egg hatching	-	Peaks at 3 days of being submerged (Keirans & Fay, 1970)
	Egg laying	Higher in half full vs full containers (Dieng et al., 2012)	-
	Wing size	-	Higher in 1 L vs 0.5 L
Water evaporation	Survival (larvae/adults)	Decreases with 100% evaporation (Alto & Juliano, 2001)	No effect (Costanzo et al., 2005)
	Egg hatching	Decreases with 100% evaporation (Costanzo et al., 2005)	No effect (Costanzo et al., 2005)
	Wing size	Increases with 100% evaporation (Alto & Juliano, 2001).	-

Discussion

This scoping review shows that quantitative data on the biological relationship between water availability and *Aedes* traits are limited, as only eleven studies have been published in the literature to date. This is a stark difference in comparison to the number of studies exploring the effect of temperature on *Aedes* traits, which are more than a hundred (Da Re et al., 2025). In terms of the *Aedes* species studied, we found four studies that used *Ae. albopictus,* five *Ae. aegypti*, and two studies that used both species in their experiments. To date, no experiments on the effect of rainfall and water availability have been conducted on *Ae. koreicus* or *Ae. japonicus*. Except for two studies published in 1952 and 1970 (Keirans & Fay, 1970; Sudia, 1952), four studies were published between 2000 and 2010 (Alto & Juliano, 2001; Costanzo et al., 2005; de Brito & Paulo Forattini, 2004; Koenraadt & Harrington, 2008) and five after 2010 (Dieng et al., 2012; Lushasi et al., 2025; Medici et al., 2011; Parker et al., 2019; Richardson et al., 2013).

This review suggests that higher rainfall intensity and longer rainfall duration increase the mortality of larvae and pupae (Dieng et al., 2012; Koenraadt & Harrington, 2008; Sudia, 1952). Rainfall may cause higher larval mortality in small breeding sites due to raindrops hitting the water surface at greater speed and splashing water out, potentially expelling juvenile mosquitoes too. It has been hypothesised that this water loss may also deplete breeding sites of nutrients, which in turn could reduce the fitness of surviving mosquitoes, including their longevity and reproductive potential (Dieng et al., 2012). For *Ae. albopictus*, this increase in mortality was observed after only 25 min of heavy rainfall compared to 10 min of light rainfall. However, since this study investigated both longer and heavy versus shorter and light rainfall treatments, it is not possible to disentangle and extrapolate the effect of rainfall duration from rainfall intensity (Dieng et al., 2012). For *Ae. aegypti*, there was no significant effect on larval survival with up to one hour of exposure to laboratory-simulated rainfall, potentially due to their strong swimming and diving skills (Koenraadt & Harrington, 2008). However, a study did observe high *Ae. aegypti* larval mortality when swimming in stronger current and for longer periods of time (Sudia, 1952). Strong currents may be created by heavy rainfall in larger breeding sites, such as catch basins, in which larvae have to swim for the duration of the rainfall event. In these cases, larval mortality can potentially be caused by energy consumption from sustained movement. Whilst there is evidence that heavy and longer rainfall can harm the survival of *Aedes* pupae and larvae, the exact mechanism inducing higher mortality remains to be elucidated and the relationships between rainfall duration and intensity and *Aedes* traits remain to be clarified.

The effect of water availability on *Aedes* lifecycle was investigated by five studies which suggested that greater water availability decreases *Aedes* survival during the aquatic stages of the life cycle, delays development and mediates the oviposition behaviour and egg hatching (Dieng et al., 2012; Lushasi et al., 2025; Medici et al., 2011; Parker et al., 2019; Richardson et al., 2013). These studies suggest that the optimal range of water volume in a breeding site for *Aedes* survival and development is below two litres, consistent with findings from entomological surveys (Alarcón-Elbal et al., 2024; Carrieri et al., 2011). Parker et al. (2019) hypothesise that developing in larger containers leads to a fitness cost due to the longer distances larvae have to cover between feeding at the bottom and breathing at the surface, leading to lower rates of survival and slower development. This hypothesis may also explain why adult emergence increased with high compared to low food concentrations for both species, since higher food density reduced foraging effort. Additionally, a study suggested that water availability might regulate oviposition, with *Ae. albopictus* females laying more eggs in containers that were half-full than in containers that were full (Dieng et al., 2012). Finally, water availability may also determine *Ae. aegypti* egg hatching success, which was found to peak *aegypti* egg hatching peaked following three days of water immersion and then declined after that (Keirans & Fay, 1970).

This review also found evidence of water evaporation modulating *Ae. albopictus'* traits. Full evaporation reduced egg viability and adult emergence for *Ae. albopictus* but not for *Ae. aegypti* (Alto & Juliano, 2001; Costanzo et al., 2005; Prasad et al., 2023). Despite *Ae. albopictus* being able to lay diapausing eggs, which are resistant to desiccation through a reduction in water loss (Urbanski et al., 2010), our results suggest that desiccation stress may still reduce the fitness of surviving *Ae. albopictus* individuals. On the other hand, *Ae. albopictus* adults that emerged after experiencing desiccation stress were larger in size, potentially explained by the reduced competition for food and access to the water surface. The extent to which evaporation-induced desiccation stress affects the life cycle and traits of *Aedes* mosquitoes, and the extent to which *Ae. albopictus* differs in their responses from *Ae. aegypti*, should be further investigated (Prasad et al., 2023). Generating experimental evidence on the effect of evaporation is particularly important given the hypothesised effect of humidity on mosquito thermal performance (Brown et al., 2023).

This scoping review highlights the limited experimental studies and the complexity of the relationship between water availability, rainfall and AIMs life history traits. On the one hand, we found evidence of rainfall directly regulating the survival of AIMs in natural breeding sites, with rainfall intensity and duration playing a role in immature mosquito survival, though further quantification for both *Ae. albopictus* and *Ae. aegypti* is needed. Moreover, rainfall frequency is likely to affect AIMs, since periodic renewal of water could trigger survival strategies such as faster egg incubation periods (Neto & Navarro-Silva, 2004). It is possible that there might be an optimal range of rainfall that allows for larval and pupal survival, which for instance for Guangzhou, in China, has been estimated to be between 131.2 and 212.8 mm of weekly rain (Liu et al., 2025). However, there are additional factors at both ends of the range which add to the complexity of defining a range. At the lower end (i.e. in the absence of rainfall), AIMs survival depends on infrastructure and on the level of human activities, including water storage behaviour and land use, since AIMs breed in both natural (rain-dependent) and artificial (rainfall-independent) containers. At the higher end of the range (i.e. floods), AIMs survival depends on rainfall, and on the increase in the breeding site availability causing a subsequent increase mosquito abundance following a high rainfall event (Madi et al., 2012; Roiz et al., 2015). Therefore, quantifying an optimal range of rainfall is a challenging task as it depends on many factors.

Characterising the direct effects of rainfall on AIMs traits, abundance and population dynamics is a current priority for both climate-sensitive modelling, forecasting, and to accurately predict short-term disease risk metrics driven by mosquito abundance (Reiner et al., 2013). This review highlights that, despite ongoing interdisciplinary efforts to better understand how climate affects mosquito population dynamics, there is an urgent need for generating experimental evidence on the effect of water availability and rainfall on AIMs. This is important not only for reconstructing past and recent observational data, but it is crucial for informing infrastructural investments in the countries that are most affected by arboviral diseases and for projecting into the future the expected effect of extreme weather events under climate change.

Conclusion

Water availability and invasive *Aedes* mosquito species have a complex relationship that has been quantitatively explored by eleven laboratory experiments to date. These studies were all performed on either *Ae. aegypti* or *Ae. albopictus*, so the effect of rainfall and water availability on *Ae. japonicus* or *Ae. koreicus* remains unexplored. Rainfall intensity is detrimental for the survival of both *Ae. aegypti* and *Ae. albopictus*, whereas water evaporation only decreases the egg viability and adult emergence of *Ae. albopictus*. Conversely, rainfall duration may affect the survival of *Aedes* species only after a long period of time, potentially due to their strong swimming skills. Our findings indicate that water availability determines female egg laying behaviour and that both species seem to have higher survival and better development in volumes of water below two litres. However, the relationship between precipitation and the population dynamics of *Aedes* species remains to be investigated, and more work is needed to identify how rainfall patterns and the different environments interact and influence the suitability, life traits and proliferation of these invasive mosquitoes, which in turn can inform vector and disease control interventions.

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Contributions

Emmanuelle Kern: screening, methodology, data extraction, data analysis, writing (original draft).
Giovanni Marini: conceptualisation, methodology, supervision, screening, writing (review and editing).
Daniele Da Re: conceptualisation, methodology, supervision, screening, writing (review and editing).
Ilaria Dorigatti: conceptualisation, methodology, supervision, screening, writing (review and editing).

Appendix

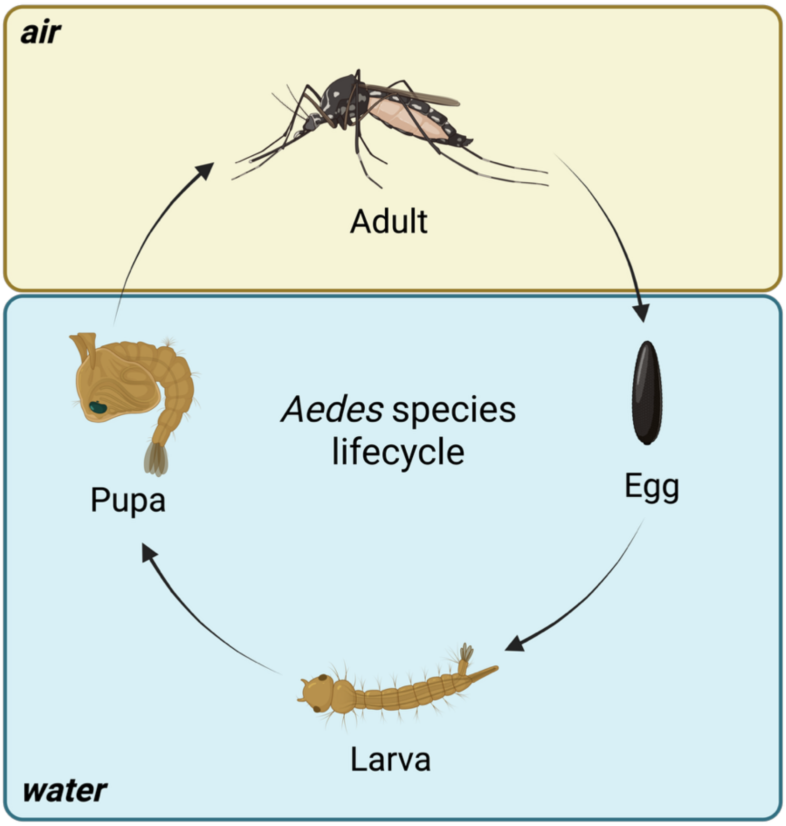

Figure S1: General lifecycle of Aedes mosquitoes (created with BioRender.com)

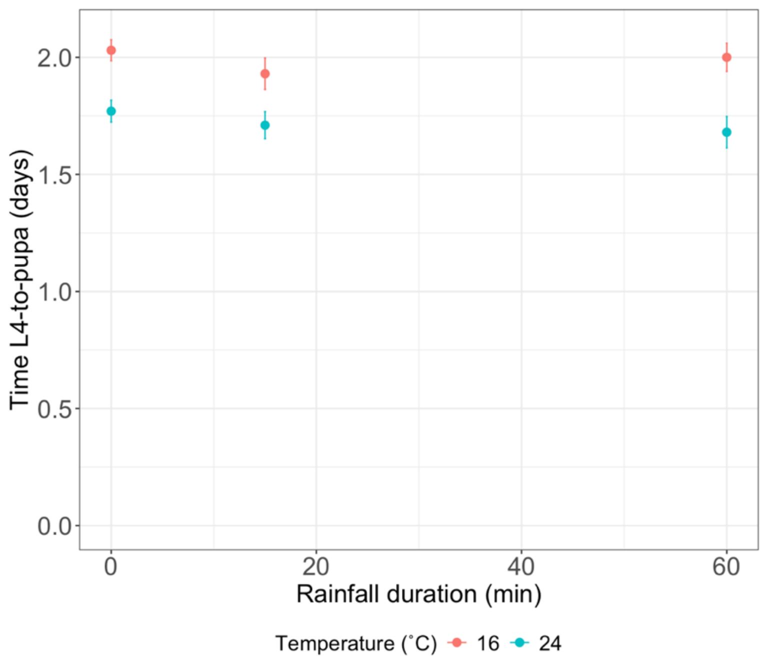

Figure S2: The effect of rainfall duration on the developmental time of *Ae. aegypti* fourth-instar larvae (L4) into pupae. Mean developmental time values when exposed to 0, 15, and 60 minutes of a constant stream of water are shown with the 95% confidence intervals. Larvae were placed in water at temperatures of 16 °C (red) or 24 °C (blue). The p-value of log-rank χ2 statistic pooled over strata (Kaplan-Meier) was 0.568 and 0.530 for the low and high temperature treatments, respectively. Data from Koenraadt and Harrington (2008).

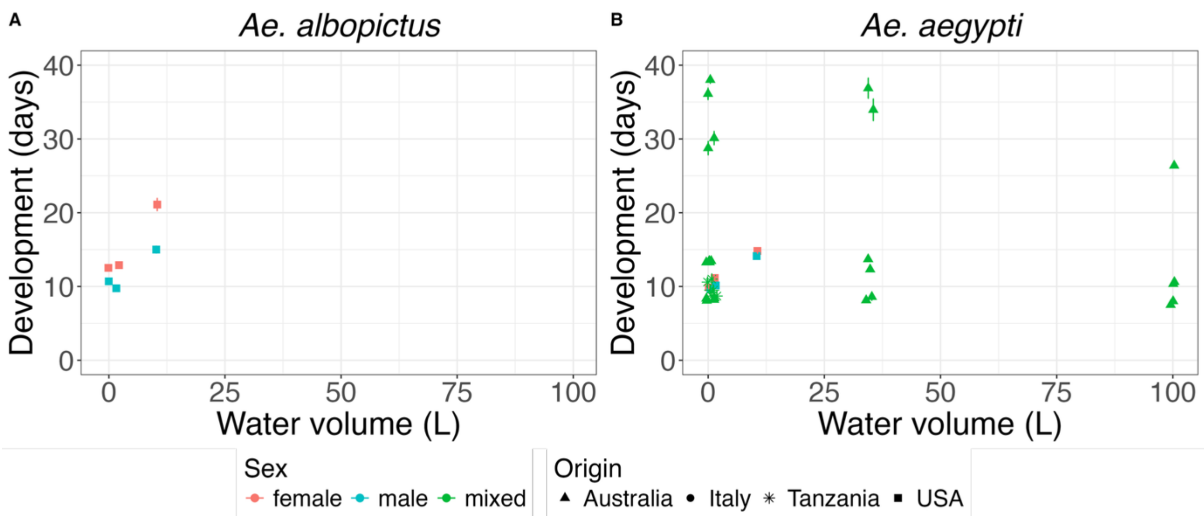

Figure S3: The effect of water availability on the development time from larvae to adulthood of *Aedes* species. (A) Mean duration of development values for *Ae. albopictus* when bred in fixed amounts of water (0.4, 2, 2.5 or 10 L) are shown with the standard error bars. The sex of the larvae, female (red), male (blue), or mixed (green) is shown. (B) Mean duration of development values for *Ae. aegypti* when bred in fixed amounts of water (0.4, 0.5, 1, 2, 10, 35, or 100 L) are shown with the standard error bars.

The sex of the larvae, female (red), male (blue), or mixed (green) are shown. The data points come from four studies conducted in Desenzano del Garda in Italy shown as circles (Medici et al., 2011), in Mississippi in the US shown as squares (Parker et al., 2019), in Cairns and Melbourne in Australia shown as triangles (Richardson et al., 2013), and in Kining'ina village in Tanzania shown as stars (Lushasi et al., 2025). The study by Medici et al. (2011) looked at the impact of breeding mosquitoes at different larval densities in a fixed volume of water, which was not shown here. The data collected in Australia has great variability because the experiments were run in February, September, and December. Larvae bred in September had significantly longer development time than those bred in the summer months of December and February (not shown).

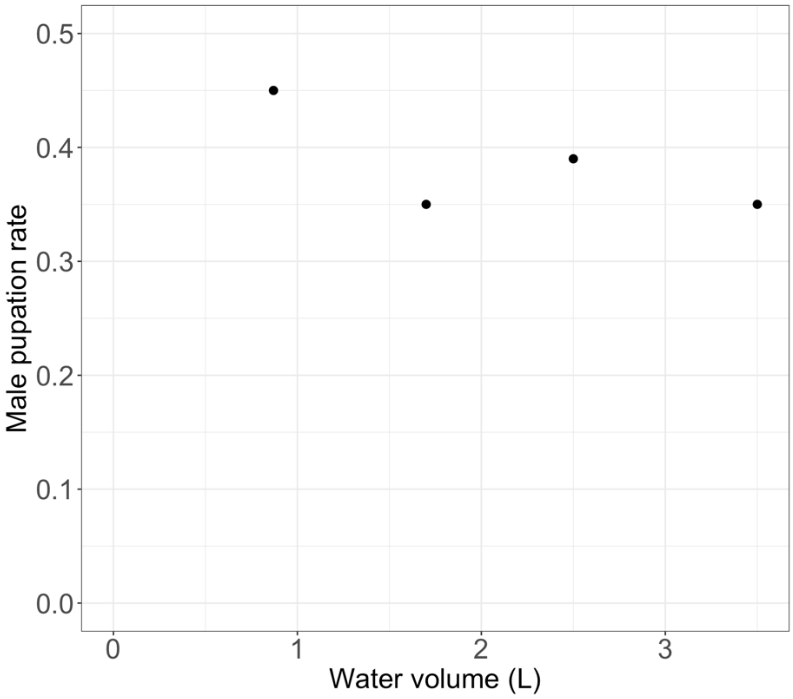

Figure S4: The effect of water availability on the male pupation rate of *Ae. albopictus*. The mean pupation rate per water volume is shown for 2,500 larvae per tray , no uncertainty measure was provided. The authors noted that the larval density did not significantly change between treatments. There was a significant decrease in the male pupation rate in increasing volumes of water (correlation coefficient R = -0.8; p = 0.045). Data from (Medici et al., 2011).

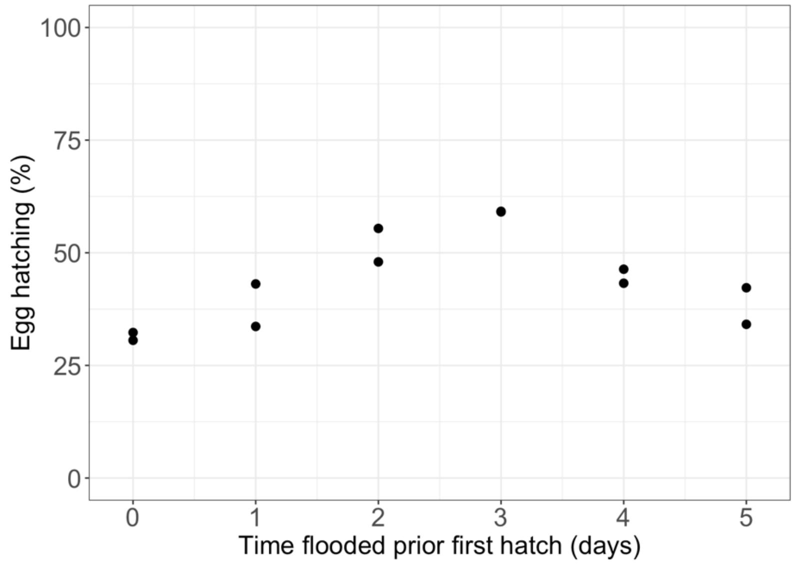

Figure S5: The effect of the number of days the eggs are flooded prior to first hatch on the hatching of *Ae. aegypti* eggs. Mean total percentage of eggs that hatched is shown, no uncertainty measure was provided. The experiments were conducted both in the sun and in the shade (not shown), but this effect was not significant on the egg hatching percentage. Data from (Keirans & Fay, 1970).

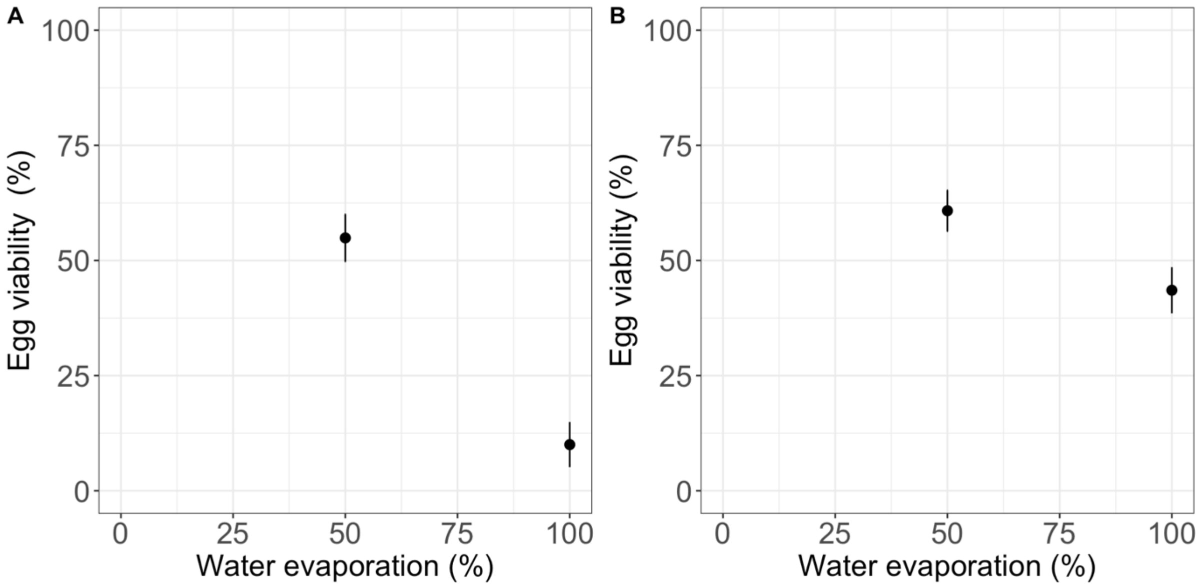

Figure S6: The effect of water evaporation on the egg viability of *Aedes* species. Mean proportions of live (A) *Ae. albopictus* and (B) *Ae. aegypti* eggs exposed to different levels of evaporation (50 or 100%) before the containers were refilled are shown with the standard error bars. Eggs exposed to the drying treatment were left two weeks without the water being refilled. The mosquitoes were caught from the field and kept at 27˚C. There were significant differences in pairwise comparisons between the 50% and 100% evaporation treatments for *Ae. albopictus* but not for *Ae. aegypti* (not shown). Data from (Costanzo et al., 2005).

Table S1: Search strategy

Topics	Keywords
Aedes aegypti	"*Aedes aegypti*" OR "Yellow Fever mosquito" OR "*Stegomyia aegypti*"
	OR
Aedes albopictus	"*Aedes albopictus*" OR "Tiger mosquito" OR "*Stegomyia albopicta*" OR "forest mosquito"
	OR
Aedes japonicus	"*Aedes japonicus*" OR "Asian Bush mosquito" OR "Asian Rock Pool mosquito" OR "*Ochlerotatus japonicus*" OR "*Hulecoeteomyia japonica*"
	OR
Aedes koreicus	"*Aedes koreicus*" OR "Korean Bush mosquito" OR "*Ochlerotatus koreicus*" OR "*Hulecoeteomyia koreica*"
AND	
Precipitation	"Rain" OR "Precipitation" OR "Water" OR "Humidity" OR "Moisture" OR "Shower" OR "Flood"

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