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Studies on the influence of water quality on community assemblage of immature mosquitoes in different ecosystems along the Vaigai river, Tamil Nadu, South India

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Abstract

Background Over the last few decades, river ecosystem is highly modified through various anthropogenic activities which are resulted to alter ecosystem functions and services. This modified ecosystem rendering conducive environment to mosquitoes through various ecological links for the self-sustaining populations. However, deciphering the community assemblage of immature mosquitoes with reference to water quality at modified ecosystem is very essential to make suitable control measure to curtail mosquito populations. In order to understand how the water quality influences the larval density, habitat specificity and community assemblage of immature mosquito populations, a study was conducted at different ecosystems (urban, semi-urban and rural) along the Vaigai river. The physico-chemical parameters such as pH, TDS, salinity, conductivity, turbidity, DO, were analyzed at each study site.

Results Our results clearly revealed that Anopheline species were highly preferred to breed less polluted habitat than Culicine species. Community assemblage by Anopheline and Culicine mosquitoes were found to be higher at all the studies whilst community assemblage by Anopheline were maximum at rural and semi-urban sites. Among the Anopheline species, *Anopheles subpictus* able to breed at high polluted habitat, particularly higher turbid level (28.49 ± 2.18 NTU) than other *Anopheles* species. *Cx. gelidus* mostly breed at sewage disposal habitats with high salinity level (1.01 ± 0.08) whilst *Cx. bitaeniorhynchus* bred in only fresh water bodies particularly low turbid habitats (3.97 ± 0.40 NTU). Grouping of immature mosquitoes based on the habitat similarity, *An. subpictus, Cx. vishnui, An. vagus, Cx. tritaeniorhynchus, Cx. gelidus* and *Cx. quinquefasciatus* were able to breed in highly polluted habitats which are resulted fell in group A than group B mosquitoes. *Cx. vishnui* and *An. subpictus* have strong habitat similarity (0.96) and can able to share their habitats with more number of Anopheline and Culicine mosquitoes.

Conclusions From the study we concluded that, *Cx. vishnui* and *An. subpictus* were most prevalent species and strong habitats similarity along the Vaigai river basin. *An. subpictus* and *An. vagus* can adapt to breed in polluted habitats and this may be adequate to extend the vectorial capacity and disease outbreak along the Vaigai river basin.

Keywords Anopheles, Culex, Water quality, Habitat similarity, Larval community assemblage, Grouping of immature mosquitoes, Vaigai river

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Background

Most of the Indian river ecosystems have been profoundly altered by various human interventions over the last few decades. Human activities such as alteration of flow regimes by construction of dams, sand mining, water pollution, etc., (CPCB, 1996; Nilsson et al., 2005; Padmalal et al., 2008; Swarnkar et al., 2021) cause serious impacts on the river ecosystem. Water pollution, which is a consequent event of anthropogenic activity, emerges as a serious problem that causes alteration of abiotic factors eventually threatening biotic communities within the river ecosystem (Amoatey & Baawain, 2019; Ishaq & Khan, 2013). This water pollution has an adverse impact on aquatic insects community, especially medically important mosquitoes which eventually effects on the epidemiology of mosquito-borne diseases (Buxton et al., 2020; Fazeli-Dinan et al., 2022; Huzortey et al., 2022; Villena et al., 2017).

Mosquitoes act as a primary vector for various diseases such as malaria, dengue, chikungunya, filariasis and Japanese encephalitis etc. (WHO, 2014). Nearly 700 million people are affected by the mosquito borne disease and more than one million deaths in every year worldwide (Chilakam et al., 2023). Bionomics of mosquitoes plays a crucial role to take suitable control measures to curtail mosquito population and disease outbreak (Wu et al., 2020). Mosquito population highly regulates by various abiotic factors, especially water pollution (Huzortey et al., 2022). Water pollution acts main driver to alter the mosquito vector composition in a habitat/area, hinder prey and predator relationship and altering breeding habitats (Huzortey et al., 2022). For instance, polluted water bodies are rendering ideal breeding habitats for Culicine than Anopheline vectors (Gunathilaka et al., 2013; Kamaladhasan et al., 2016). The polluted habitat, particularly high turbid water affects the predatory efficiency due to low visibility of prey (Homski et al., 1994; Paaijmans et al., 2008). Last few decades, several studies reported that Anopheline vectors have adapted to breed in polluted water bodies across the world. For instance, *An. gambiae* (Awolola et al., 2007; Ossè et al., 2019), *An. culicifacies* (Gunathilaka et al., 2013, 2015), *An. coluzzii* (Kudom, 2015; Ossè et al., 2019), *An. subpictus* (Gunathilaka et al., 2015; Kamaladhasan et al., 2016), *An. stephensi* (Fazeli-Dinan et al., 2022) were breeding in polluted water bodies. In our previous studies, we reported that human activities within the river bed rendering conducive environment for mosquito breeding through various ecological link for the maintenance of self-sustained mosquito populations along the river ecosystem (Kamaladhasan et al., 2016). These anthropogenic activities are highly modified the river ecosystem especially water quality along the river basin. Therefore, deciphering the how water quality influence on the mosquito ecology at modified river ecosystem is very essential to understand the epidemiology of mosquito-borne diseases and curtail mosquito population. Hence, the present study is aimed to study the community assemblage and habitat similarity of immature mosquito population with reference to water quality at different habitats along the Vaigai River basin.

Methods

Study sites

The Vaigai river bisects the Madurai city into two halves and flows downstream for 145 km and passes 127 km upstream originating from the Cumbum Valley of the Western Ghats. In order to understand the influence of water quality on habitat specificity and community assemblage of immature mosquito populations, three different study sites viz. urban (Madurai city: 9° 55′ N, 78° 07′ E), semi-urban (Sholavandan: 10° 01′ N, 77° 57′ E) and rural (Thenoor; 9° 59′ N; 78° 00′ E) were selected and observations were made on a 5 km linear stretches along the Vaigai river in each study site.

Immature mosquito sample collection

The immature mosquito populations were studied at three different ecosystems viz., urban, semi-urban and rural study sites along the Vaigai river basin. Observations were made during the pre-monsoon, monsoon and post-monsoon seasons of 2013–2014. The larval density of *Anopheles, Culex* and *Aedes* were calculated by using dipper method in all the study sites. Based on the immature mosquito populations in habitat, the number of dips per habitat was determined. The number of dips varied from 3 to 10 per habitat depending on the immature mosquito population. The sampling was done on alternate days in all the study sites during the entire period of the study. The immature mosquitoes were collected and transferred to the laboratory, and the emerged adults were collected and identified with the help from Center for Research in Medical Entomology (CRME), Madurai. The species composition and relative frequency of mosquitoes were calculated and the average larval density was measured at all the study sites. The presence and absence of predators in each study site was noted for each sample.

Physico-chemical analysis of water

The physico-chemical parameters such as pH, total dissolved solids (TDS), salinity, conductivity, turbidity, dissolved oxygen (DO) were analyzed using water analysis kit (Systronics, 371). The free carbon dioxide (free CO_2) and total alkalinity (TA) were analyzed by standard titration method. Temperature and water depth were measured in habitats with standard instruments.

Data analysis

Grouping of immature mosquitoes based on their habitat similarities

The collected immature mosquitoes were grouped based on their breeding habitat similarity. Data was analyzed according to the method proposed by Devi and Jauhari (2007) and Stein et al. (2011). The operational taxonomic units (OTUs) were given based on the vegetative and non-vegetative habitat types. The vegetation types include the presence of floating algae, filamentous algae, host plant (*Cynodon dactylon*, *Saccharum spontaneum*, *Cyperus rotundus*, *Typha* sp., *Polygonum glabrum*, *Ipomoea aquatica*, *Arundo donax*, *Eichhornia crassipes*, *Azolla* sp., *Marsilea* sp. and *Lemna* sp.), algal bloom and the absence of vegetation. The non-vegetative habitat types include rock pools, animal hoofs, waste dumping (cups, polythene bags, etc.), detritus (stumps, leaves, etc.) and cement tanks. The type of habitat sharing among immature mosquitoes was considered as an OTU. The presence or absence of predators inhabiting with immature mosquitoes was also considered as another OTU. Individual OTUs were assigned for each of water quality parameters (pH, TDS, salinity, turbidity, conductivity, DO, free CO2, TA, water depth and temperature) of breeding habitats for each species. All the larval habitat characteristics were subdivided into groups and codified as 1/0 (=presence/absence). A matrix of data consisting of 21 rows for mosquito species and 135 columns for breeding habitats was developed in tabular form based on the codified data. This matrix data was used to analyze the similarity among all OTUs using the Jaccard's coefficient of association (JC). From the similarity matrix, OTUs were grouped and depicted in the form of a dendrogram.

Results

Relative frequencies of immature mosquitoes at different ecosystem during seasons

The relative frequency of mosquitoes showed greater variations among the study sites and seasons throughout the entire study period. *Cx. vishnui* was found to be a pervasive species which showed a higher relative frequency (38.46%) than other mosquitoes at urban sites during the pre-monsoon season. In contrast to urban sites, *An. subpictus* had a high relative frequency in semi-urban and rural study sites during the pre-monsoon season (35.82% and 27.06% respectively). During monsoon season, *Cx. vishnui* had the highest relative frequency (28.10%) in the urban sites, while *An. culicifacies* were found to have a higher relative frequency in semi-urban (18.82%) and rural study sites (27.27%). During post-monsoon season, *An. subpictus* was observed as a more common species and had higher relative frequencies than other mosquito species in all study sites. (Table 1).

Average larval density at different study sites during seasons

In urban study site, pre-monsoon and post-monsoon seasons significantly influenced the *Anopheles* larval density than monsoon season ($F = 6.38$; $p < 0.05$). In the case of *Culex* larval density, monsoon season seemed to have high influence than the other two seasons ($F = 8.059$; $p < 0.05$). Oddly, *Aedes* larval density was not found to be influenced by any seasons ($F = 1.123$; $p > 0.05$). In semi-urban study site, *Anopheles* larval density was strongly influenced by pre-monsoon season than other two seasons ($F = 34.25$; $p < 0.05$). *Culex* larval density was not influenced by any seasons ($F = 3.318$; $p > 0.05$). In rural study site, pre-monsoon and post-monsoon seasons significantly influenced the *Anopheles* larval density than monsoon season ($F = 4.457$; $p < 0.05$). *Culex* larval density was influenced by both pre-monsoon and monsoon seasons than post-monsoon season ($F = 3.587$; $p < 0.05$). *Aedes* larval density was not influenced by any seasons ($F = 0.380$; $p > 0.05$) (Fig. 1).

Average larval density and presence or absence of predators

In urban site, *Anopheles* and *Culex* larval density was found to be higher in habitats without predators when compared to the habitats with predators during the pre-monsoon and monsoon seasons. Higher *Anopheles* larval density was recorded in habitats without predators when compared to habitats with predators whereas *Culex* larval density was observed to be maximum in habitats with predators rather than without predators during post-monsoon season. In semi-urban site, higher *Anopheles* larval density was recorded in habitats without predators when compared to habitats with predators during pre-monsoon and monsoon seasons whereas *Anopheles* larval density was higher in habitats with predators during post-monsoon season. *Culex* larval density found to be high in the presence of predators during the pre-monsoon and monsoon seasons. In rural site, *Anopheles* larval density was greater in habitats without predators than with predators during monsoon and post-monsoon seasons. *Culex* larval density was found to be high in habitats without predators during all seasons (Fig. 2).

Inhabitation of predators along with immature mosquitoes under different vegetation

A total of seven aquatic predators were found to co-exist with immature mosquito populations in all the

Table 1 Mosquito relative frequency (%) at different ecosystems along the Vaigai river, Tamil Nadu

S. no.	Name of the species	Relative frequency (%)—pre-monsoon (August & September 2013)			Relative frequency (%)—monsoon (November & December 2013)			Relative frequency (%)—post-monsoon (May & June 2014)		
		Urban	Semi-urban	Rural	Urban	Semi-urban	Rural	Urban	Semi-urban	Rural
1.	*Anopheles subpictus*	33.65	35.82	27.06	19.10	12.94	11.36	46.67	31.43	52.63
2.	*Anopheles vagus*	–	10.45	3.53	4.49	12.94	9.09	–	8.57	2.63
3.	*Anopheles culicifacies*	–	8.20	25.88	–	18.82	27.27	–		13.17
4.	*Anopheles annularis*	–	0.75	–	–	1.17	–	–		–
5.	*Anopheles barbirostris*	–	2.24	–	–	8.24	3.41	–	5.71	–
6.	*Anopheles peditaeniatus*	–	–	4.71	1.12	2.35	1.14	–	–	–
7.	*Anopheles pallidus*	–	–	1.17	–	–	1.14	–	–	–
8.	*Anopheles splendidus*	–	–	1.17	–	–	–	–	–	–
9.	*Anopheles stephensi*	–	–	–	–	2.35	–	–	–	–
10.	*Culex pseudovishnui*	0.96	–	1.18	4.49	–	1.14	–	–	–
11.	*Culex gelidus*	3.85	2.24	–	8.99	2.35	1.14	6.67	11.43	–
12.	*Culex tritaeniorhynchus*	10.58	11.19	9.41	12.36	8.25	1.14	–	–	–
13.	*Culex quinquefasciatus*	11.54	4.48	1.18	13.48	4.71	–	3.33	14.29	–
14.	*Culex vishnui*	38.46	19.40	16.47	28.10	12.94	12.50	36.67	22.86	21.05
15.	*Culex bitaeniorhynchus*	–	4.48	3.53	–	11.77	17.04	–	5.71	5.26
16.	*Culex infula*	–	–	–	4.49	1.17	–	–	–	–
17.	*Culex fuscocephala*	–	–	–	–	–	–	3.33	–	–
18.	*Lutzia fuscana*	–	0.75	–	1.13	–	1.14	–	–	–
19.	*Fredwardsius vittatus*	0.96	–	4.71	–	–	4.54	–	–	5.26
20.	*Stegomyia aegypti*	–	–	–	2.25	–	–	3.33	–	–
21	*Aedeomyia catasticta*	–	–	–	–	–	7.95	–	–	–

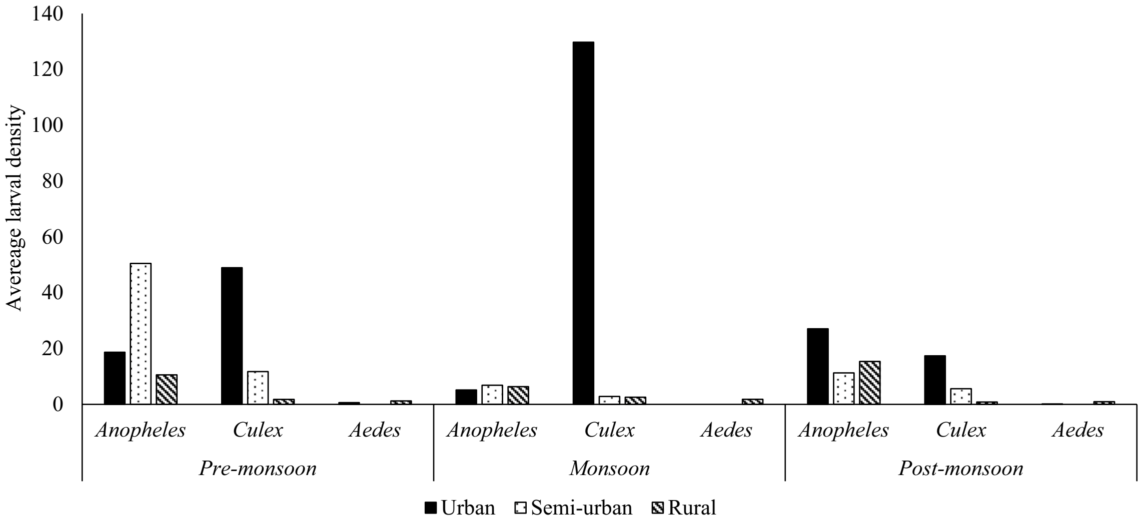

Fig. 1 Average larval density of Anopheline and Culicine species along the Vaigai river, Tamil Nadu

study sites during the study period. The aquatic predators such as backswimmer, dragonfly, damselfly and diving beetles were observed in all sites. Water bugs were mainly noticed in urban sites whereas fishes and tadpoles were recorded in semi-urban and rural sites. Among the predators, backswimmers were observed in various aquatic vegetation types such as filamentous algae, floating algae, *Cyperus rotundus*, *Polygonum glabrum*, *E.*

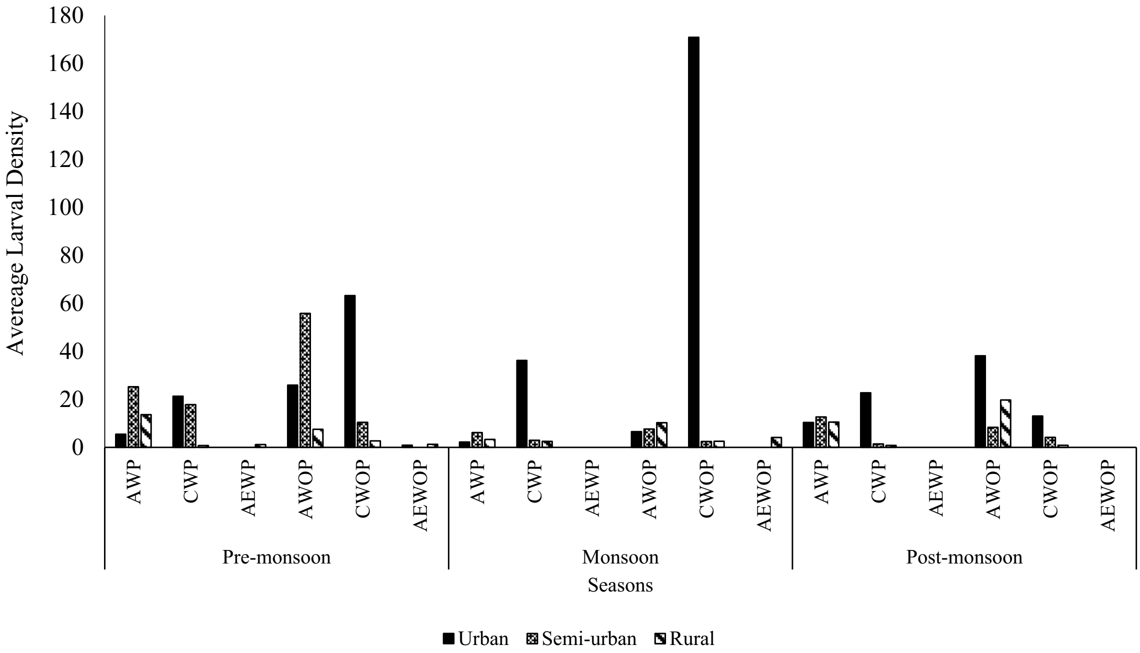

Fig. 2 Average larval density of Anopheline and Culicine species in habitats with and without predators. AWP, *Anopheles* larval density with predators; CWP, *Culex* larval density with predators; AEWP, *Aedes* larval density with predators; AWOP, *Anopheles* larval density without predators; CWOP, *Culex* larval density without predators; AEWOP, *Aedes* larval density without predators

crassipes, *Ipomoea aquatica*, *Cynodon dactylon*, *Azolla* sp., detritus, algal bloom and in area devoid of vegetation. Dragonfly and damselfly were mainly noticed in sites dominated by filamentous algae. Water bugs were mainly noticed to exist in roots of *E. crassipes*. Backswimmer inhabited with more number of immature mosquitoes (18/ 21) followed by dragonfly (13/ 21) and water bugs (10/ 21) (Table 2).

Relative frequency of predators at different ecosystems

During pre-monsoon season, backswimmer showed greater relative frequency at urban (53.33%) and rural sites (61.11%) whereas dragonfly had high relative frequency in semi-urban site (42.11%). Dragonfly had high relative frequency at semi-urban (35.29%) and rural sites (48.15%) during monsoon season. In urban site, backswimmer had maximum relative frequency during monsoon season (40.74%). Dragonfly was found to have high relative frequency in semi-urban site (50%) whereas backswimmer was higher at urban site (38.46%) during post-monsoon season. Backswimmer and dragonfly showed almost equal relative frequency during post-monsoon season in rural site (Table 3).

Percentage co-occurrence of predators along with immature mosquito populations

Predators were found to co-exist with immature mosquito populations in all the study sites during the entire study period. At urban study site, the percentage of predator co-occurrence along with larvae was found to be higher during post-monsoon followed by pre-monsoon and monsoon seasons. The percentage co-occurrence of predators was gradually increasing from pre-monsoon to post-monsoon season at rural study site. During the pre-monsoon and monsoon seasons, the percentage of predator co-occurrence was higher in rural whereas the maximum percentage of predator co-occurrence was noted in urban followed by rural and semi-urban site during post-monsoon season (Fig. 3).

Community assemblage of immature mosquitoes at different study sites

Community assemblage of immature mosquito populations was found to be strongly influenced by seasons in all the sites. During pre-monsoon season, community assemblage of *Anopheles* with *Culex* (45.71%) was found to be higher followed by *Anopheles* community and *Aedes* community at rural site. In semi-urban site, habitat occupied by *Anopheles* with *Culex* was higher followed by *Anopheles* community during pre-monsoon season. Community assemblage by *Culex* species alone was not observed in semi-urban and rural sites during pre-monsoon season. In urban site, assemblage of *Anopheles* with *Culex* (64%) was maximum followed by *Culex* alone (30%); *Anopheles* alone (4%); *Aedes* with *Anopheles* and *Culex* community (2%) during pre-monsoon

Table 2 Inhabitant of predators along with immature mosquitoes in the Vaigai river, Tamil Nadu

Name of the species	Without predators	Backswimmer	Dragonfly	Damselfly	Water bug	Diving beetle	Fish	Tadpole
Anopheles subpictus	+	+	+	+	+	+	+	+
Anopheles vagus	+	+	+	−	−	+	+	+
Anopheles culicifacies	+	+	+	−	−	+	+	+
Anopheles annularis	−	+	+	−	−	−	−	+
Anopheles barbirostris	+	+	+	−	−	+	−	−
Anopheles peditaeniatus	+	+	+	+	+	−	+	+
Anopheles pallidus	+	−	−	−	−	−	−	−
Anopheles splendidus	−	+	−	−	−	−	−	−
Anopheles stephensi	+	−	+	−	−	−	−	−
Culex pseudovishnui	+	+	−	+	+	−	−	−
Culex gelidus	+	+	−	−	+	−	+	−
Culex tritaeniorhynchus	+	+	+	+	+	+	−	+
Culex quinquefasciatus	+	+	+	−	+	+	+	+
Culex vishnui	+	+	+	+	+	+	−	+
Culex bitaeniorhynchus	+	+	+	+	+	−	+	+
Culex infula	+	+	+	+	+	−	−	−
Culex fuscocephala	−	+	−	−	−	−	−	−
Lutzia fuscana	+	+	−	−	−	−	−	−
Fredwardsius vittatus	+	+	−	−	−	+	−	−
Stegomyia aegypti	+	−	−	−	+	−	−	−
Aedeomyia catasticta	+	+	+	−	−	−	−	−

season. *Anopheles* with *Culex* assemblage was observed to be higher in all the study sites during monsoon season. Community assemblage by *Anopheles* species alone was found to be greater in semi-urban and rural site when compared to *Culex* community alone during monsoon season. Community assemblage by *Anopheles* species alone was not observed in urban site during monsoon season. During post-monsoon season, *Anopheles* community was greater at rural (45.45%) site followed by *Anopheles* with *Culex* (40.91%). *Anopheles* sharing their habitats with *Culex* (44.44%) mosquitoes were found to be higher at semi-urban whilst community assemblage by *Anopheles* alone and *Culex* alone was almost in equal proportion at semi-urban sites during post-monsoon season. In urban site, community assemblage of *Anopheles* with *Culex* was observed to be greater followed by *Anopheles* community and *Culex* community during post-monsoon season (Table 4).

Physico-chemical analysis of water at different study sites

Water quality parameters varied among the sites during all seasons. During the pre-monsoon season, pH, conductivity, dissolved oxygen, total alkalinity and salinity varied in all the study sites. Total dissolved solids, turbidity, free carbon dioxide was higher in the urban site than others. During the monsoon season, pH was found to be higher in rural site when compared to other sites. Salinity, conductivity, turbidity was higher at urban site than other sites whereas total alkalinity, free carbon dioxide and TDS varied in all the sites. During post-monsoon season, pH was found to be higher in rural site than semi-urban and urban sites. Salinity and conductivity didn't vary among the study sites whereas total alkalinity was higher in semi-urban site than other sites. TDS and turbidity were found to be greater in urban site than semi-urban and rural sites. Free carbon dioxide was found to be lower in rural site when compared to urban and semi-urban sites (Table 5).

Water quality versus mosquitoes

Anopheles diversity was found to be higher in semi-urban followed by rural and urban sites. When comparing with *Culex* mosquitoes, *Anopheles* mosquitoes seemed to prefer less polluted water bodies. *An. subpictus* was found to breed in polluted water bodies with a wide range of TDS (range = 0.53–1010), salinity (range = 0.05–4.39), turbidity (range = 0.38–316) and total alkalinity (range = 0.25–450). *An. vagus* and *An. peditaeniatus* were also able to breed in high turbid water (range = 0.93–124 & 1.1–85) than other Anopheles species. Among the *Anopheles* species, *An. annularis* and *An. stephensi* was found to breed in less turbid habitats at low temperature (Table 6).

Table 3 Relative frequency of predators at different study sites along the Vaigai river, Tamil Nadu

Common name	Order	Urban			Semi-urban			Rural		
		Pre-monsoon (%)	Monsoon (%)	Post-monsoon (%)	Pre-monsoon (%)	Monsoon (%)	Post-monsoon (%)	Pre-monsoon (%)	Monsoon (%)	Post-monsoon (%)
Back swimmer	Hemiptera	53.33	40.74	38.461	36.84	23.529	33.33	61.11	29.63	41.176
Dragonfly	Odonata	6.66	3.703	15.38	42.105	35.29	50	5.55	48.15	41.176
Damselfly	Odonata	–	11.11	7.692	5.26	–	16.666	–	–	5.82
Diving beetle	Coleoptera	13.33	18.518	23.076	5.26	–	–	16.66	–	5.88
Water bug	Hemiptera	26.66	25.92	15.384	–	–	–	–	3.7	–
Tadpole	Gadiformes	–	–	–	10.526	11.764	–	5.55	7.41	–
Fish		–	–	–	–	23.529	–	11.11	–	5.882

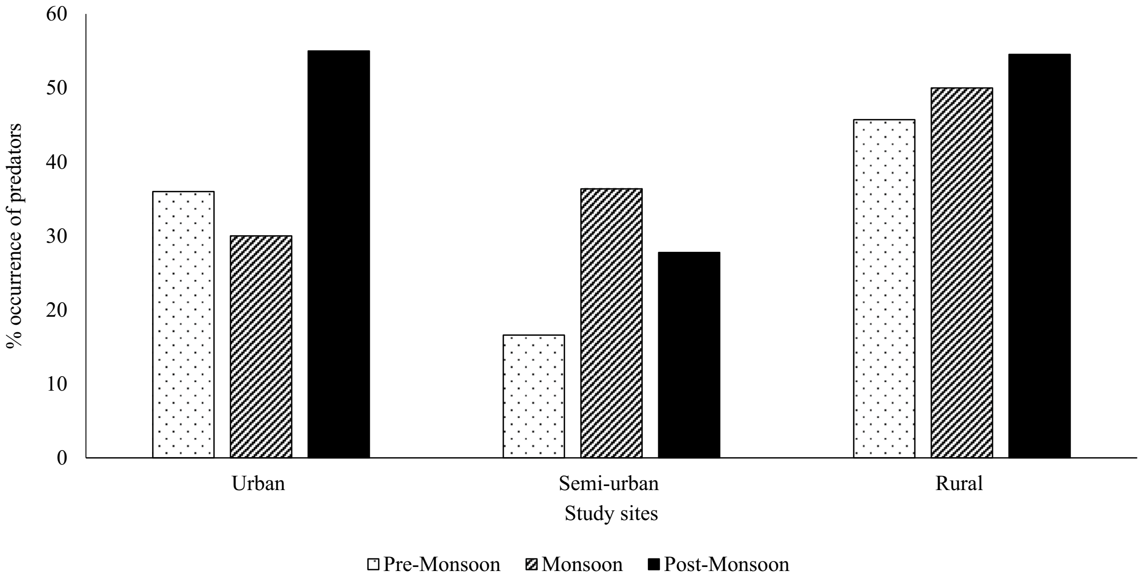

Fig. 3 Percentage co-occurrence of predators along with immature mosquito population along the Vaigai river, Tamil Nadu

Table 4 Community assemblage of immature mosquitoes at different study sites along the Vaigai river, Tamil Nadu

Species co-occurrence	% of species co-occurrence of immature population in aquatic habitats								
	Pre-monsoon			Monsoon			Post-monsoon		
	Rural	Semi-urban	Urban	Rural	Semi-urban	Urban	Rural	Semi-urban	Urban
Anopheles only	42.86	29.63	4	22.73	34.29	–	45.45	27.78	30
Anopheles + *Culex*	45.71	70.37	64	54.54	57.14	52.5	40.91	44.44	40
Culex only	–	–	30	13.64	8.57	42.5	4.55	27.78	25
Aedes only	11.43	–	–	–	–	–	–	–	–
Aedes + *Anopheles*	–	–	–	4.55	–	–	9.09	–	–
Aedes + *Anopheles* + *Culex*	–	–	2	4.54	–	5	–	–	5

Table 5 Physico-chemical characteristics of water at different study sites along the Vaigai river, Tamil Nadu

Parameters	Pre-monsoon			Monsoon			Post-monsoon		
	Urban	Semi-urban	Rural	Urban	Semi-urban	Rural	Urban	Semi-urban	Rural
pH	7.93 ± 0.04^{c}	8.07 ± 0.02^{b}	8.21 ± 0.06^{a}	7.79 ± 0.08^{b}	8.07 ± 0.05^{b}	8.45 ± 0.06^{a}	7.81 ± 0.08^{b}	7.79 ± 0.04^{b}	8.34 ± 0.12^{a}
TDS (ppm)	109.47 ± 3.97^{a}	35.65 ± 1.58^{b}	27.56 ± 1.60^{b}	124.75 ± 6.74^{a}	52.15 ± 2.75^{b}	31.98 ± 1.1^{c}	365.31 ± 50.12^{a}	99.62 ± 5.42^{b}	97.55 ± 17.10^{b}
SAL (ppt)	1.06 ± 0.04^{a}	0.41 ± 0.02^{b}	0.29 ± 0.02^{c}	1.19 ± 0.07^{a}	0.45 ± 0.02^{b}	0.32 ± 0.01^{b}	1.10 ± 0.15^{a}	0.83 ± 0.05^{a}	0.75 ± 0.13^{a}
CON (ms)	1.96 ± 0.07^{a}	0.76 ± 0.03^{b}	0.50 ± 0.03^{c}	4.25 ± 0.47^{a}	0.89 ± 0.05^{b}	0.62 ± 0.02^{b}	2.27 ± 0.31^{a}	1.74 ± 0.09^{a}	1.57 ± 0.24^{a}
TUR (NTU)	70.28 ± 5.09^{a}	10.35 ± 1.19^{b}	12.1 ± 1.53^{b}	36.52 ± 5.05^{a}	5.29 ± 0.59^{b}	3.77 ± 0.82^{b}	49.74 ± 8.33^{a}	16.58 ± 2.63^{b}	19.42 ± 6.04^{b}
DO (ppm)	9.63 ± 0.08^{a}	6.33 ± 0.15^{b}	4.44 ± 0.09^{c}	4.94 ± 0.37^{a}	4.47 ± 0.15^{a}	4.81 ± 0.13^{a}	2.32 ± 0.23^{b}	3.39 ± 0.27^{a}	3.51 ± 0.27^{a}
FCO_2 (mg/l)	99.23 ± 6.05^{a}	24.82 ± 1.13^{b}	36.89 ± 2.12^{b}	172.89 ± 2.50^{a}	77.82 ± 6.22^{b}	32.14 ± 2.65^{c}	123.89 ± 2.31^{a}	91.36 ± 7.47^{ab}	70.25 ± 16.48^{b}
TA (mg/l)	307.42 ± 9.28^{a}	144.39 ± 3.56^{b}	103.87 ± 2.63^{c}	152.87 ± 6.68^{a}	79.24 ± 3.04^{b}	51.86 ± 1.73^{c}	73.75 ± 4.98^{b}	108.13 ± 4.75^{a}	8.05 ± 0.5^{c}
WD (cm)	7.44 ± 0.27^{b}	8.34 ± 0.32^{b}	10.16 ± 0.68^{a}	10.27 ± 0.49^{a}	7.12 ± 0.51^{b}	7.27 ± 0.53^{b}	10.31 ± 1.09^{a}	5.71 ± 0.59^{b}	6.79 ± 0.67^{b}
TEM (ºC)	30.04 ± 0.16^{a}	28.65 ± 0.17^{b}	30.32 ± 0.13^{a}	27.57 ± 0.09^{a}	26.20 ± 0.14^{c}	26.66 ± 0.12^{b}	29.25 ± 0.18^{b}	29.99 ± 0.18^{ab}	30.19 ± 0.27^{a}

TDS, total dissolved solids; SAL, salinity; CON, conductivity; TUR, turbidity; DO, dissolved oxygen; FCO_2, free carbon dioxide; TA, total alkalinity; WD, water depth; TEM, temperature

Table 6 Physico-chemical characteristics of water in breeding habitats of Anopheline and Culicine species

Name of the species	Parameters									
	pH	TDS (ppm)	SAL (ppt)	CON (ms)	TUR (NTU)	DO (ppm)	FCO_2 (mg/l)	TA (mg/l)	WD (cm)	TEM (°C)
ASU	8.09 ± 0.02 (6.95–10.08)	8.64 ± 6.02 (0.53–1010)	0.64 ± 0.02 (0.05–4.39)	1.31 ± 0.06 (0.10–13.9)	28.49 ± 2.18 (0.38–316)	5.45 ± 0.12 (0.1–12.9)	74.15 ± 3.89 (0–539)	136.76 ± 4.20 (0.2.5–450)	7.84 ± 0.22 (1.3–31.6)	28.88 ± 0.09 (24–34.5)
AVA	8.16 ± 0.05 (7.38–9.69)	52.63 ± 3.38 (0.56–164)	0.49 ± 0.03 (0.14–1.46)	1.36 ± 0.19 (0.24–13.9)	13.99 ± 2.23 (0.93–124)	5.49 ± 0.21 (1.4–12.9)	59.43 ± 6.47 (0–429)	104.78 ± 4.99 (5–300)	7.05 ± 0.40 (2.1–29.3)	27.75 ± 0.19 (24–32.7)
ACU	8.28 ± 0.04 (7.19–10.08)	35.64 ± 1.39 (7.6–164)	0.34 ± 0.01 (0.14–1.25)	0.65 ± 0.02 (0.24–2.64)	7.35 ± 0.83 (0.11–85)	4.89 ± 0.09 (0.4–11.3)	38.37 ± 1.99 (0–154)	78.86 ± 2.58 (5–200)	8.52 ± 0.46 (1.6–47.8)	27.95 ± 0.15 (24–32.5)
AAN	8.00 ± 0.02 (7.95–8.07)	45.62 ± 9.23 (22.6–66.9)	0.48 ± 0.02 (0.41–0.52)	0.83 ± 0.13 (0.49–1.13)	2.75 ± 0.26 (1.8–3.7)	5.18 ± 0.13 (4.9–5.5)	57.2 ± 21.55 (11–132)	102.83 ± 4.51 (95–125)	5.76 ± 1.01 (3.8–10.2)	24.58 ± 0.22 (24–25.4)
ABA	7.86 ± 0.07 (7.19–8.85)	58.88 ± 5.59 (23.8–154)	0.49 ± 0.04 (0.26–1.2)	1.02 ± 0.09 (0.52–2.62)	8.07 ± 1.04 (0.84–24)	5.41 ± 0.35 (2.6–11.3)	77.56 ± 11.86 (11–264)	102.07 ± 7.96 (50–182.5)	7.68 ± 0.45 (3.4–13.5)	26.89 ± 0.23 (24.5–30.6)
APE	8.07 ± 0.10 (7.52–8.85)	38.95 ± 6.59 (13.7–130)	0.35 ± 0.05 (0.14–1.02)	1.76 ± 0.86 (0.24–14.4)	15.22 ± 5.87 (1.1–85)	5.55 ± 0.48 (3.6–12.3)	53 ± 5.77 (11–110)	93.41 ± 7.36 (52.5–150)	10.27 ± 1.15 (4.5–27.3)	28.73 ± 0.46 (24.5–32.1)
APA	8.58 ± 0.08 (8.19–8.8)	30.78 ± 0.83 (27.6–33.4)	0.32 ± 0.01 (0.3–0.33)	0.57 ± 0.03 (0.46–0.67)	6.5 ± 1.81 (2.2–13)	4.57 ± 0.31 (3.4–5.6)	12.37 ± 4.37 (0–33)	88.62 ± 15.38 (52.5–152)	4.88 ± 0.69 (2.1–8.1)	27.73 ± 0.62 (25.7–30.4)
ASP	7.94 ± 0.01 (7.93–7.94)	22.86 ± 0.14 (22.6–23.1)	0.24 ± 0.01 (0.24–0.25)	0.42 ± 0.01 (0.41–0.42)	4.4 ± 1.20 (3.1–6.8)	4.56 ± 0.08 (4.4–4.7)	26.76 ± 2.56 (22–30.8)	70.83 ± 4.16 (62.5–75)	16.3 ± 4.01 (11.2–24.2)	31.1 ± 0.1 (31–31.3)
AST	8.16 ± 0.08 (7.95–8.37)	49.13 ± 7.64 (32–66.9)	0.38 ± 0.06 (0.25–0.52)	0.83 ± 0.13 (0.54–1.13)	3.5 ± 0.50 (1.8–5.2)	5.36 ± 0.05 (5.2–5.5)	71.5 ± 15.75 (33–132)	75.33 ± 9.88 (50–100)	4.35 ± 0.29 (3.8–5.6)	25.5 ± 0.35 (24.2–26.6)
FVI	9.52 ± 0.09 (8.18–10.3)	41.93 ± 16.15 (4.78–312)	0.34 ± 0.12 (0.05–2.36)	0.82 ± 0.27 (0.10–5.46)	30.80 ± 11.81 (1.1–268)	4.44 ± 0.39 (1.3–10.5)	13.68 ± 2.68 (0–44)	93.63 ± 28.21 (2.5–575)	7.25 ± 0.49 (2–11.2)	30.25 ± 0.28 (27.9–33.5)
SAE	7.64 ± 0.15 (7.19–8.17)	334.43 ± 116.34 (152–790)	1.27 ± 0.13 (0.75–1.53)	2.25 ± 0.19 (1.5–2.66)	60.33 ± 21.4 (9.3–124)	1.51 ± 0.23 (0.5–2.2)	328 ± 30.40 (231–429)	126.43 ± 23.07 (75–217.5)	7.06 ± 1.94 (2.9–16.7)	27.79 ± 0.17 (27.2–28.6)

ASU, *Anopheles subpictus*; AVA, *Anopheles vagus*; ACU, *Anopheles culicifacies*; AAN, *Anopheles annularis*; ABA, *Anopheles barbirostris*; APE, *Anopheles peditaeniatus*; APA, *Anopheles pallidus*; ASP, *Anopheles splendidus*; AST, *Anopheles stephensi*; FVI, *Fredwardsius vittatus*; SAE, *Stegomyia aegypti*

Fredwardsius vittatus was found to breed under high pH with low free carbon dioxide when compared to other mosquitoes. *Cx. bitaeniorhynchus* and *Cx. infula* bred at high pH (8.19 ± 0.04 & 8.49 ± 0.13) when compared to other *Culex* mosquitoes. *Cx. fuscocephala* bred at high total dissolved solids (570.5 ± 2.5) and free carbon dioxide levels (170.5 ± 16.5). *Cx. infula* was observed at high conductivity (6.87 ± 1.45) and high dissolved oxygen levels (9.57 ± 0.99) when compared to other *Culex* mosquitoes. Among *Culex* mosquitoes, *Cx. vishnui* (34.07 ± 2.41) bred under high turbid water followed by *Cx. quinquefasciatus* (29.55 ± 2.99) and *Cx. gelidus* (26.26 ± 3.28). *Cx. gelidus* was found to breed only in sewage water whereas *Cx. bitaeniorhynchus* bred only in low turbid fresh water bodies (Table 7).

Grouping immature mosquito population by habitat similarity

The different species of mosquitoes were arranged into two major groups using the values of coefficient of association presented in the similarity matrix (Table 8). According to cluster analysis (Fig. 4), *An. subpictus*, *Cx. vishnui*, *An. vagus*, *Cx. tritaeniorhynchus*, *Cx. gelidus*, and *Cx. quinquefasciatus* fell under group A. The group B was divided into two sub groups namely group B1 and B2. Sub-group B1 consists of *An. annularis*, *An. stephensi*, *An. splendidus*, *An. pallidus*, *Cx. fuscocephala* and *Aedeomyia catasticta* whereas *An. peditaeniatus*, *An. culicifacies*, *An. barbirostris*, *Cx. infula*, *Cx. pseudovishnui*, *Cx. bitaeniorhynchus*, *Lutzia fuscana*, *Stegomyia aegypti* and *Fr. vittatus* was found under group B2. Based on habitat similarity analysis, *An. subpictus* and *Cx. vishnui* were found to have the highest association (0.961). The similarity values within the species for Group A are as follows: *An. vagus*/*Cx. tritaeniorhynchus* (0.899), *Cx. vishnui*/*Cx. tritaeniorhynchus* (0.856), *Cx. tritaeniorhynchus*/*Cx. quinquefasciatus* (0.848) and *Cx. quinquefasciatus*/*Cx. gelidus* (0.830). In Group A, *An. subpictus* had strongest habitat similarity with *Cx. vishnui* (0.961), *Cx. tritaeniorhynchus* (0.833), *Cx. quinquefasciatus* (0.818), *An. vagus* (0.816), and *Cx. gelidus* (0.731). In group B, mosquito species pairs showing high similarity were *An. culicifacies* with *Cx. bitaeniorhynchus* (0.832), *An. peditaeniatus* with *Cx. infula* (0.782), *An. peditaeniatus* between *Cx. pseudovishnui* (0.773), *An. barbirostris* with *Lt. fuscana* (0.760), *Cx. infula* with *Cx. pseudovishnui* (0.742) (Table 8). In group A, *An. subpictus* and *Cx. vishnui* were found almost in all the types of immature habitats at all the sites during the study period. It is inferred that these two species had a wide range of adaptability to habitats dominated by *E. crassipes*, *C. rotundus*, *S. spontaneum*, *I. aquatica*, *P. glabrum*, filamentous algae, floating algae, *C. dactylon*, *Marsilea* sp., algal bloom, *Arundo donax*, *Lemna* sp. and *Azolla* sp. *An. subpictus*, *An. vagus*, *Cx. vishnui*, *Cx. tritaeniorhynchus*, *Cx. gelidus* and *Cx. quinquefasciatus* were able to breed in polluted water bodies typically associated with high turbidity. As a result, the immature mosquitoes of group A have been sharing their habitats with more number of distant or closely related mosquito species along the Vaigai river (Table 9). In group B1, mosquitoes preferred unique ecological habitats along the river. *An. annularis*, *An. stephensi*, *An. splendidus*, *An. pallidus* and *Ad. catasticta* bred in filamentous algae dominated sites. These mosquitoes bred at low level of turbid water when compared to group A. Immature mosquitoes of group B1 utilize limited ecological niches which led us to conclude that B1 mostly don't share their habitat with other species. In group B2, few more ecological habitats were occupied by mosquitoes when comparing to group B1. *An. peditaeniatus* was found to breed under various vegetation types such as floating algae, filamentous algae, *E. crassipes*, *C. rotundus*, *S. spontaneum* and *Typha* sp. *Cx. pseudovishnui* utilized aquatic vegetation such as *E. crassipes*, *C. rotundus*, *I. aquatica*, *P. glabrum*, filamentous algae and *C. dactylon* as their breeding habitats. The immature of *An. barbirostris* was collected from floating algae, filamentous algae, *Cynodon dactylon*, algal bloom, *C. rotundus*, *S. spontaneum*, *Lemna* sp. and *Azolla* sp. dominated sites. *An. culicifacies* bred in floating algae, filamentous algae, *C. rotundus*, *S. spontaneum*, detritus, *Typha* sp. and even in open water. *Lt. fuscana* immature was recorded in *C. dactylon*, *C. rotundus* and floating algae dominated sites. *Cx. infula* and *Cx. bitaeniorhynchus* preferentially bred in filamentous algae dominated habitats. Immature of the Group B2 was found to breed in slightly turbid water than group B1.

Discussion

The Vaigai river is highly altered by various human activities which have consequently led to support immature mosquito populations by providing strong ecological links for their sustenance within the ecosystem (Kamaladhasan et al., 2016). Among various human activities, sewage disposal into river was found to influence water quality thereby affecting the structure and function of the ecosystems. Water pollution in river ecosystem causes loss of biodiversity by altering species composition from natural to pollutant tolerant community (Xu et al., 2013). In the present study, water quality parameters considered in this study have been found to influence the distribution and composition of mosquito populations along the Vaigai river ecosystem. Among the water quality parameters, pH plays a significant role in the habitat preference of Anopheline species. Almost all Anopheles species have been observed to breed in habitats with pH ranges

Table 7 Physico-chemical characteristics of water in breeding habitats of immature Culicine species

Name of the Species	Parameters									
	pH	**TDS (ppm)**	**SAL (ppt)**	**CON (ms)**	**TUR (NTU)**	**DO (ppm)**	**FCO$_2$ (mg/l)**	**TA (mg/l)**	**WD (cm)**	**TEM (°C)**
CBI	8.19 ± 0.04 (7.23–8.86)	44.05 ± 1.93 (15.6–102)	0.42 ± 0.01 (0.19–0.8)	0.80 ± 0.03 (0.46–1.75)	3.97 ± 0.40 (0.15–18)	5.05 ± 0.16 (1–11.3)	42.17 ± 3.64 (0–176)	77.35 ± 3.92 (7.5–175)	7.31 ± 0.46 (1.6–31)	27.43 ± 0.19 (24–31.6)
CVI	7.97 ± 0.03 (6.95–10.3)	92.37 ± 4.39 (0.56–790)	0.78 ± 0.03 (0.1–3.78)	1.87 ± 0.10 (0.19–14.5)	34.07 ± 2.41 (0.5–316)	6.03 ± 0.15 (0.1–13.7)	91.96 ± 4.15 (0–429)	169.80 ± 5.81 (2.5–650)	8.13 ± 0.20 (1.8–29.3)	28.83 ± 0.09 (24–34.5)
CTR	7.91 ± 0.03 (7.23–8.9)	57.97 ± 3.55 (0.56–179)	0.58 ± 0.03 (0.14–1.53)	2.14 ± 0.25 (0.24–14.5)	21.98 ± 2.88 (0.36–119)	6.56 ± 0.24 (0.4–16.6)	85.84 ± 7.35 (5.5–429)	155.83 ± 7.26 (55–425)	8.83 ± 0.43 (2.1–29.3)	28.37 ± 0.16 (24–33)
CPS	7.59 ± 0.05 (7.36–8.08)	41.09 ± 1.70 (28.1–50.9)	0.34 ± 0.01 (0.29–0.38)	3.08 ± 0.47 (0.47–5.14)	6.42 ± 1.35 (1.6–21)	6.18 ± 0.48 (3.9–12.6)	90.09 ± 13.84 (33–253)	96.45 ± 7.49 (62.5–150)	13.82 ± 1.63 (5.5–29.3)	27.82 ± 0.27 (26.1–30.7)
CGE	7.63 ± 0.04 (7.28–8.5)	102.25 ± 6.16 (4.3–176)	1.01 ± 0.08 (0.24–4.17)	2.19 ± 0.15 (0.56–5.14)	26.26 ± 3.28 (1.9–88)	6.49 ± 0.42 (0.8–11.5)	111.74 ± 7.55 (13.2–253)	210.15 ± 15.45 (50–425)	10.34 ± 0.77 (3.6–29.3)	29.11 ± 0.25 (24.2–33.2)
CIN	8.49 ± 0.13 (7.97–9.37)	79.21 ± 8.32 (48.9–126)	0.64 ± 0.06 (0.41–0.98)	6.87 ± 1.45 (0.81–13.9)	5.29 ± 0.8 (2.9–12)	9.57 ± 0.99 (4.4–13.7)	83.2 ± 12.57 (0–140)	99.17 ± 8.23 (55–145)	10.32 ± 0.88 (5.5–17.4)	27.42 ± 0.17 (26.4–28.6)
CQU	7.76 ± 0.03 (7.3–8.65)	86.96 ± 4.66 (0.53–165)	0.93 ± 0.05 (0.2–4.17)	1.57 ± 0.07 (0.49–2.77)	29.55 ± 2.99 (0.36–132)	6.34 ± 0.34 (0.2–16.6)	103.53 ± 9.79 (11–462)	187.75 ± 9.65 (62.5–425)	8.63 ± 0.35 (2.8–26.7)	28.07 ± 0.18 (24–33)
CFU	7.43 ± 0.01 (7.42–7.43)	570.5 ± 2.5 (568–573)	0.54 ± 0.01 (0.54–0.55)	1.09 ± 0.01 (1.09–1.1)	7.9 ± 1.7 (6.2–9.6)	1.9 ± 0.2 (1.7–2.1)	170.5 ± 16.5 (154–187)	75 ± 0.0 (75–75)	8.05 ± 1.25 (6.8–9.3)	28.4 ± 0.2 (28.2–28.6)
LFU	7.88 ± 0.15 (7.43–8.38)	89.16 ± 4.91 (71.5–101)	0.75 ± 0.07 (0.52–0.94)	1.46 ± 0.07 (1.21–1.65)	25.24 ± 5.14 (2.4–38)	4.22 ± 1.03 (1.4–8.1)	122.37 ± 33.09 (44–253)	150.31 ± 17.25 (110–225)	9.87 ± 0.78 (4.6–12.6)	28.91 ± 0.78 (25.7–31.7)
ACA	8.11 ± 0.11 (7.5–8.67)	33.91 ± 0.97 (30.5–42.3)	0.33 ± 0.01 (0.29–0.4)	0.59 ± 0.01 (0.54–0.71)	3.29 ± 0.62 (0.96–8.6)	4.45 ± 0.14 (3.6–5.2)	14.93 ± 2.11 (5.5–33)	55.89 ± 1.56 (50–70)	7.92 ± 0.76 (4.2–18.9)	26.09 ± 0.26 (24.3–27.8)

CBI, *Culex bitaeniorhynchus*; CVI, *Culex vishnui*; CTR, *Culex tritaeniorhynchus*; CPS, *Culex pseudovishnui*; CGE, *Culex gelidus*; CIN, *Culex infula*; CQU, *Culex quinquefasciatus*; CFU, *Culex fuscocephala*; LFU, *Lutzia fuscana*; ACA, *Aedeomyia catasticta*

Table 8 Similarity matrix for the operative taxonomic units of different mosquito calculated using coefficient of association

Mosquito species	ASU	AVA	ACU	AAN	ABA	APE	APA	ASP	AST	CPS	CGE	CTR	CQU	CVI	CBI	CIN	CFU	LFU	FVI	SAE	ACA
ASU	1.00																				
AVA	0.82	1.00																			
ACU	0.72	0.81	1.00																		
AAN	0.38	0.50	0.57	1.00																	
ABA	0.61	0.74	0.78	0.66	1.00																
APE	0.66	0.76	0.78	0.61	0.73	1.00															
APA	0.32	0.44	0.48	0.59	0.59	0.52	1.00														
ASP	0.23	0.31	0.34	0.49	0.34	0.41	0.42	1.00													
AST	0.31	0.41	0.47	0.77	0.57	0.53	0.63	0.48	1.00												
CPS	0.56	0.68	0.65	0.59	0.69	0.77	0.56	0.46	0.51	1.00											
CGE	0.73	0.77	0.74	0.49	0.71	0.73	0.41	0.34	0.43	0.72	1.00										
CTR	0.83	0.89	0.76	0.46	0.71	0.76	0.41	0.29	0.41	0.69	0.78	1.00									
CQU	0.82	0.83	0.75	0.48	0.74	0.70	0.42	0.31	0.42	0.63	0.83	0.85	1.00								
CVI	**0.96**	0.82	0.71	0.39	0.62	0.66	0.32	0.24	0.32	0.58	0.73	0.86	0.80	1.00							
CBI	0.62	0.72	0.83	0.65	0.72	0.79	0.58	0.44	0.59	0.73	0.70	0.69	0.69	0.60	1.00						
CIN	0.49	0.60	0.59	0.63	0.66	0.78	0.51	0.43	0.61	0.74	0.61	0.59	0.54	0.51	0.67	1.00					
CFU	**0.20**	0.28	0.30	0.46	0.40	0.29	0.38	0.36	0.39	0.38	0.32	0.26	0.27	0.21	0.37	0.40	1.00				
LFU	0.46	0.62	0.64	0.60	0.76	0.64	0.57	0.38	0.54	0.68	0.68	0.59	0.59	0.48	0.67	0.61	0.49	1.00			
FVI	0.60	0.59	0.57	0.42	0.58	0.54	0.47	0.29	0.36	0.48	0.63	0.59	0.59	0.63	0.52	0.56	0.32	0.56	1.00		
SAE	0.53	0.56	0.49	0.42	0.56	0.47	0.41	0.28	0.36	0.51	0.53	0.55	0.58	0.54	0.48	0.52	0.41	0.52	0.54	1.00	
ACA	0.36	0.46	0.54	0.68	0.58	0.60	0.68	0.64	0.69	0.58	0.45	0.46	0.47	0.39	0.64	0.59	0.35	0.51	0.36	0.41	1.00

ASU, *Anopheles subpictus*; AVA, *Anopheles vagus*; ACU, *Anopheles culicifacies*; AAN, *Anopheles annularis*; ABA, *Anopheles barbirostris*; APE, *Anopheles peditaeniatus*; APA, *Anopheles pallidus*; ASP, *Anopheles splendidus*; AST, *Anopheles stephensi*; CPS, *Culex pseudovishnui*; CGE, *Culex gelidus*; CTR, *Culex tritaeniorhynchus*; CQU, *Culex quinquefasciatus*; CVI, *Culex vishnui*; CBI, *Culex bitaeniorhynchus*; CIN, *Culex infula*; CFU, *Culex fuscocephala*; LFU, *Lutzia fuscana*; FVI, *Fredwardsius vittatus*; SAE, *Stegomyia aegypti*; ACA, *Aedeomyia catasticta*

between 6.95 and 10.08. Similarly, Akeju et al. (2022) reported that the pH of the breeding habitats of Anopheles species ranges between 6.05 and 8.23. This clearly reveals that Anopheline species mainly prefer to select their oviposition sites with a slightly acidic and slightly alkaline pH environment (Akeju et al., 2022; Getachew et al., 2020). Total dissolved solid has been found to be higher in urban sites than semi-urban and rural sites which are resulted alter the composition and dominance of mosquito species. In the present study, the diversity and dominance of *Culex* mosquitoes were highest in urban sites when compared to Anopheles species. These results clearly showed that *Culex* mosquitoes are able to breed with high total dissolved solids content, whereas Anopheles mosquitoes mainly opt to breed with less total dissolved solids content. These results are concurred with the findings of Vanlalhruaia et al. (2014) reported that, Anopheles species prefer habitats with less total dissolved solid compared to *Culex* mosquitoes, which have strong associations with high dissolved matter and total dissolved solid. However, in the present study, *An. subpictus* can breed in a habitat with a high level of total dissolved solids range between 0.53 and 1010, compared to other Anopheles species. This finding was in agreement with the report of Abai et al. (2015), where Anopheles mosquitoes have a strong association with high levels of total dissolved solid (1261.40 1214.31). Among the water quality parameters, salinity and conductivity can be considered as predictive variables for the existence of mosquito species. The increase in salinity and conductivity has resulted in a reduction in species diversity and an increase in the density of salinity-tolerant species (Gopalakrishnan et al., 2013; Nikookar et al., 2017). This was in agreement with the report of the present study, the diversity of Anopheles species was observed to be higher in breeding habits with less level of salinity and conductivity when compared to *Culex* species. However, among the Anopheles species, the density of *An. subpictus* gradually increased with the increase in salinity and conductivity. This is clearly showed that the *An. subpictus* have adapted to tolerate the high salinity environment condition. Among the *Culex* species, *Culex gelidus* can able to thrive under in high salinity habitats. Similar results were also observed in the *Cx. tarsalis* and *Cx. quinquefasciatus* (Kengne et al., 2019; Patrick & Bradley, 2000). Turbidity also plays a crucial role in the identification

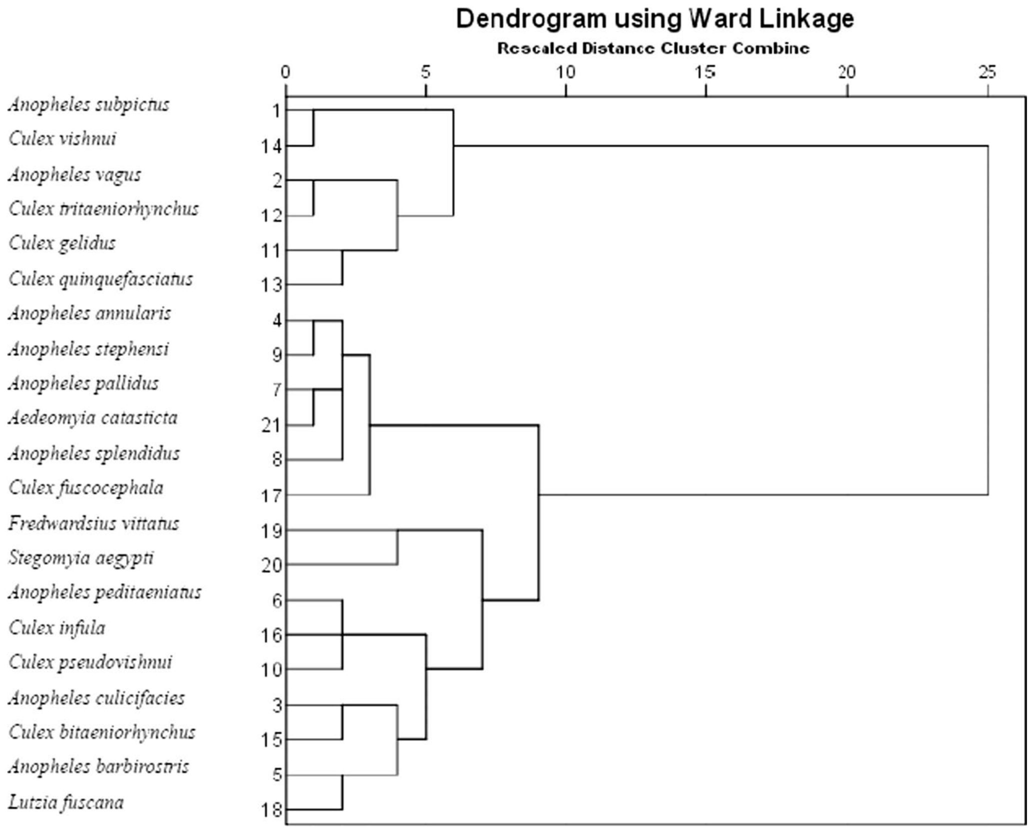

Fig. 4 Grouping of immature mosquitoes based on the habitat similarity using dendrogram

of breeding habitats for Anopheline and Culicine. The breeding of Anopheline species was observed in habitats with lower turbidity levels, while that of *Culex* species was observed in habitats with high turbidity levels. This result is concurred with the finding of Sattler et al. (2005) reported that Anopheles mosquito larvae were absent in habitats with turbid environments, whereas *Culex* species were much more likely to breed in such habitats. However, *An. subpictus* is able to breed and has a greater density in habitats with high levels of turbidity than other *Anopheles* species in the present study. This result is not in agreement with the finding of Seal and Chatterjee (2023), reported that, *An. subpictus* larvae were found to be higher in less turbid habitats when compared to highly turbid environments.

Water quality also plays a significant role on the community assemblage of immature mosquitoes along the Vaigai river basin. Community assemblage by Anopheles have found to be higher in rural sites and semi-urban sites when compared to urban sites. In rural and semi-urban sites, water bodies are less polluted which are eventually to breed by Anopheles species than polluted water bodies. This result is supported by earlier studies reported that Culicine immatures were found in polluted water and Anopheline immatures were found in less polluted water (Okorie, 1978; Okogun, 2005; Sattler et al., 2005; Devi & Jauhari, 2007; Impoinvil et al., 2008; Mwangangi et al., 2010). Community assemblage by Anopheles along with *Culex* species were found to be higher in all the study sites during all the season. In the present study, habitat similarity index was found to be higher between *An. subpictus* and *Cx. vishnui* (0.96) and shared their habitats with a greater number of distant or closely related species which are resulted to increased community assemblage by Anopheles along with *Culex* species along the Vaigai river basin. This result is coincided with the finding of Devi and Jauhari (2007) reported that *Cx. mimeticus* and *An. maculatus* have strong association with their habitats. This result was similar to the findings of Minakawa et al. (1999), Caillouet et al. (2008) who also reported that, 58.6% and 42.9% of the habitats were co-existed by Anopheline and Culicine species respectively. Grouping of immature mosquitoes based on their habitat similarity is clearly revealed that Mosquitoes belonging to group A were much more like to breed polluted water bodies when compared to Group B mosquito species. Among the group A mosquito species, *An. subpictus and An. vagus* have adapted to breed in polluted water

Table 9 Co-occurrence of immature mosquito species in a breeding habitat along the Vaigai river, Tamil Nadu

Name of the species	Co-occurrence of immature mosquitoes
Anopheles culicifacies	An. sub, An. vag, Cx. bit, Cx, tri, Cx. vis, Cx. qui, An. spl, An. pal, Cx. psv, An. ped, An. ann, An. bar, Ad. cat, Fr. vit
Anopheles subpictus	Cx. vis, Cx, tri, An. vag, Cx. inf, St. aeg, Lt. fus, Cx. qui, Cx. gel, Cx. psv, An. cul, Cx. bit, An. pal, Ad. cat, Ae. vit, An. ste, An. ann, An. ped, An. bar, Cx. fus
Anopheles vagus	Cx. vis, An. sub, St. aeg, Cx, tri, Cx. inf, Cx. gel, Cx. psv, An. cul, An. bar, Cx. bit, Ad. cat, An. ste, An. ped, Cx. qui, An. ann
Anopheles barbirostris	An. cul, Cx. vis, Cx. bit, Ad. cat, An. vag, An. sub, An. ped, Cx. tri, Cx. qui
Anopheles pallidus	An. cul, Cx. vis, An. sub, Ad. cat, An. ped, Cx. bit
Anopheles peditaeniatus	Cx. vis, Cx, tri, An. pal, Ad. cat, Cx. bit, An. cul, An. bar, An. sub, An. vag, Cx. qui
Anopheles annularis	An. sub, Cx. vis, An. cul, An. ste, An. vag, Cx. bit, Cx, tri, Cx. qui
Anopheles stephensi	An. cul, Cx. vis, An. vag, An. sub, An. ann
Anopheles splendidus	An. cul
Culex bitaeniorhynchus	Cx. tri, An. cul, Cx. vis, An. sub, Ad. cat, An. ped, An. vag, An. bar, Cx. psv, Cx. qui, An. ann, An. pal
Culex vishnui	An. sub, Cx. tri, Cx. gel, Cx. psv, An. vag, Cx. inf, St.aeg, Lt. fus, Cx. qui, An. ped. An. bar, An. cul, Cx. bit, An. pal, Ae. vit, An. ste, An. ann, Cx. fus
Culex tritaeniorhynchus	Cx. qui, Cx. vis, An. sub, Cx. gel, St. aeg, Cx. psv, An. vag, An. ped, Cx. inf, An. bar, An. cul, Cx. bit, An. ann
Culex pseudovishnui	Cx. vis, Cx. tri, An. sub, Cx. gel, An. vag, An. cul, Cx. bit, Cx. qui
Culex gelidus	Cx. vis, Cx. tri, An. sub, An. vag, Cx. psv, Cx. qui, St. aeg, Lt. fus
Lutzia fuscana	Cx. vis, An. sub, Cx. gel, Cx. qui
Aedeomyia catasticta	An. bar, An. cul, An. vag, An. sub, Cx. bit, An. pal, An. ped
Fredwardsius vittatus	An. cul, Cx. vis, An. sub
Culex infula	Cx. vis, An. sub, Cx. tri, An. vag
Culex quinquefasciatus	Cx. vis, An. sub, Cx. tri, Cx. gel, An. cul, Cx. bit, An. bar, Cx.psv, An. ped, An. ann, An. vag, Lt. Fus
Stegomyia aegypti	Cx. vis, An. sub, An. vag, Cx. tri, Cx. gel
Culex fuscocephala	Cx. vis, An. sub

An. sub, *Anopheles subpictus*; An. cul, *Anopheles culicifacies*; An. vag, *Anopheles vagus*; An. bar, *Anopheles barbirostris*; An. pal, *Anopheles pallidus*; An. ped, *Anopheles peditaeniatus*; An. ann, *Anopheles annularis*; An. ste, *Anopheles stephensi*; An. spl, *Anopheles splendidus*; Cx. bit, *Culex bitaeniorhynchus*; Cx. vis, *Culex vishnui*; Cx. tri, *Culex tritaeniorhynchus*; Cx. psv, *Culex pseudovishnui*; Cx. gel, *Culex gelidus*; Lt. fus, *Lutzia fuscana*; Ad. cat, *Aedeomyia catasticta*; Fr. vit, *Fredwardsius vittatus*; Cx. inf, *Culex infula*; Cx. qui, *Culex quinquefasciatus*; St. aeg, *Stegomyia aegypti*; Cx. fus, *Culex fuscocephala*

bodies in addition to fresh water habitats. Similarly, some of the Anopheline species has been observed to breed in polluted water habitats across the world. For instances, *An. subpictus* was noted to breed in polluted habitats at urban ecosystem (Gunathilaka et al., 2015). Drainage habitats with waste water is an ideal breeding habitats for *An. culicifacies* (Gunathilaka et al., 2013). *An. gambiae* and *An. coluzzii* can able to breed wide range of water bodies including polluted water (Awolola et al., 2007; Ossè et al., 2019). In the present study, *An. subpictus*, *Cx. vishnui*, *An. vagus*, *Cx. tritaeniorhynchus*, *Cx. gelidus*, and *Cx. quinquefasciatus* were more prevalent species and might be significant role on the mosquito born disease outbreak along the Vaigai river basin.

Conclusions

The results of this study clearly revealed that physiochemical parameters determine the species composition and community assemblage of immature mosquitoes along the Vaigai river basin. The habitat preference of Anopheline species is greatly influenced by physiochemical parameters like pH, total dissolved solid, salinity, conductivity, and turbidity. Among the immature mosquito species, *An. subpictus*, and *Cx. vishnui* were the most prevalent species and had strong habitat similarity, which led to an increase in the community assemblage of Anopheline and Culicine species along the river ecosystem. In the present study showed for the first time *An. subpictus* and *An. vagus* can adapt to breed in polluted habitats and this may be adequate to extend the vectorial capacity and disease outbreak along the Vaigai river basin.

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Author contributions

NK performed the experiments under the supervision of SC, who also collected data, analyzed the data, and wrote the original manuscript. SS, PM and JB gave technical support provided expert advice and critical review and RM curated the data.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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