Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(4): 3191 – 3211 (2025)
www.ejabf.journals.ekb.eg

Climate Change Scenarios for Prediction of Freshwater Snails Using Classification and Regression Tree (CART): Egyptian Delta Governorates as Case Study

Amal Saad-Hussein[1], Nahed M.M. Ismail[2], Naglaa Zanaty[3], Suzan E. Ali [2], Asmaa Abdel-Motleb[2*]

[1]Environmental and Occupational Medicine Department, Environment and Climate Change Research Institute, National Research Centre, Giza, Egypt
[2]Environmental Research Departmet, Theodor Bilharz Research Institute, Giza, Egypt
[3]National Authority for Remote Sensing and Space Sciences, Cairo, Egypt

***Corresponding Author: a_abdelmotlb@yahoo.com**

ARTICLE INFO

Article History:
Received: June 3rd, 2025
Accepted: Aug. 6, 2025
Online: Aug. 27, 2025

Keywords:
Climate change,
Freshwater snails,
CART analysis,
Atmospheric temperature,
Physico-chemical parameters,
SDG 3, 13, 14

ABSTRACT

Global warming due to climate change may alter the characteristics of freshwater habitats. Rising water temperatures increase evaporation and decrease oxygen concentration, which in turn may affect the survival and reproduction of freshwater gastropod snails. This study aimed to predict the presence and abundance of freshwater snails in six Delta governorates (Kafr El-Sheikh, Damietta, Menoufia, Gharbia, Dakahlia, and Beheira) during two survey periods (2010–2016 and 2019–2020). Predictions were made in relation to physicochemical water parameters—temperature, electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), and pH—as well as annual maximum (Tmax) and minimum (Tmin) atmospheric temperatures, using Classification and Regression Tree (CART) analysis. The field survey revealed that the highest percentages of collected live snails were recorded in Beheira (48.9%, 44.7%, and 34.5% during winter, summer, and autumn, respectively) and in Damietta during spring (29%). CART analysis identified Tmax as the most important variable influencing snail occurrence and distribution in five governorates (Damietta, Menoufia, Gharbia, Dakahlia, and Beheira), while Tmin was most influential in two governorates (Kafr El-Sheikh and Dakahlia). In Damietta, conductivity together with Tmax were the only two variables found to be 100% significant. These results suggest that changing atmospheric temperatures due to global warming may alter the presence and distribution of freshwater snails in their habitats. Therefore, atmospheric temperature is considered a key determinant that plays a crucial role in shaping the diversity of freshwater snails, including those that transmit diseases.

INTRODUCTION

Global warming, a result of climate change, is one of the greatest problems facing the world today. Several studies have indicated that the increase of greenhouse gases in the atmosphere (primarily carbon dioxide, methane, and nitrous oxide) plays an important role in raising atmospheric temperatures. The climate change crisis has increased the average global temperature, leading to more frequent high-temperature extremes such as heat waves, which may raise aquatic ecosystem temperatures and reduce water quality **(Ali, 2022; EC, 2022; UN, 2022)**.

Aquatic snails are essential organisms within freshwater ecosystems, playing significant roles in both public and veterinary health **(Abdel-Wareth & Sayed, 2023)**. However, some species transmit serious diseases to humans and livestock, including schistosomiasis and fasciolosis. A key objective of freshwater ecology is to analyze how communities of freshwater species are organized and how environmental factors influence their distribution. As noted by **Pemola *et al.* (2015)**, snail communities are affected by dominant physicochemical conditions, which dictate their abundance, presence, and seasonal fluctuations. These conditions include dissolved oxygen levels, pH, water temperature, and substrate characteristics **(Rai & Jauhari, 2016)**.

Climate change also affects the spread of vector-borne diseases by influencing pathogens, vectors, hosts, and transmission pathways. The speed of development and spread of these diseases will significantly depend on temperature and geographical distribution. Over the last few decades, significant regional changes in vector-borne disease distribution have been observed in temperate, peri-Arctic, Arctic, and tropical highland areas. Thus, adaptation strategies will be required to mitigate future risks **(Ibrahim *et al.*, 2025)**. Temperature is one of the main climatic variables directly affecting water- and vector-borne diseases in ecosystems **(Yimiao *et al.*, 2024)**. Vector bionomics are strongly influenced by temperature alongside other system elements such as host behavior, development, and pathogen survival. Much of the knowledge regarding these interactions is derived from mathematical models **(Glidden *et al.*, 2024)**, though some direct evidence has been documented **(Fouque & Reeder, 2019)**.

Several studies in Egypt have shown that temperature significantly influences the distribution of freshwater snails in specific governorates **(Saad *et al.*, 2014; Abdel Kader *et al.*, 2016; El-Deeb *et al.*, 2017; Abdel-Wareth & Sayed, 2023)**. In Zimbabwe, **Pedersen *et al.* (2014)** demonstrated that temperature may play an important role in determining snail habitat suitability. They developed a biologically based model incorporating climatic and environmental parameters for the freshwater snails *Bulinus globosus*, *Biomphalaria pfeifferi*, and *Lymnaea natalensis*. Their results suggested that climate change could reduce the spatial distribution of suitable snail habitats, with the exception of *B. pfeifferi*, which may increase by 2055 before declining towards 2100. Overall, the net effect of climate change on emerging diseases will reflect temperature impacts on all life stages of both hosts and parasites **(Paull & Johnson, 2011)**.

Various models have been developed to understand possible scenarios of climate change impacts on freshwater snail distribution. In Eastern Africa, **McCreesh *et al.* (2015)** applied a climate change model to assess the stages of *Schistosoma mansoni* and its intermediate snail host, finding high sensitivity to the relationships between air and water temperature and snail mortality rates. **Ngarakana-Gwasira *et al.* (2016)** modeled the effects of climate variables on schistosomiasis severity in South Africa and Zimbabwe, identifying an optimum transmission temperature of approximately 23°C. Schistosomiasis transmission in Sub-Saharan Africa is also significantly affected by physicochemical parameters such as pH and conductivity, in addition to climatic factors **(Adekiya *et al.*, 2020)**. Similarly, **Ayob *et al.* (2025)** used ecological models (2040–2070 and 2070–2100) to predict the future distribution of schistosomiasis snail vectors in South Africa using bioclimatic variables.

Recently, classification and regression tree (CART) analysis has gained attention. Unlike traditional methods, CART can uncover complex interactions between predictors that may otherwise be overlooked. This makes CART a powerful analytical tool with significant potential utility. Although it requires more time and effort to apply and interpret, its increasing use suggests it will continue to be one of the best available approaches for analyzing ecological data **(Breiman *et al.*, 1984; Roger, 2000; Bittencourt & Robin, 2003)**.

Previous research on the effect of climate change on water quality **(Ismail *et al.*, 2023)**, conducted at six selected Delta governorates, revealed through ArcGIS mapping that water quality is strongly influenced by climatic factors, particularly atmospheric temperature. Maximum air temperature (Tmax) showed the greatest impact on parameters such as water temperature, dissolved oxygen, and heavy metals. Using geostatistical methods, spatial distribution provided a visual representation of key water quality drivers. This also allowed predictions of climatic impacts on water quality **(Getachew *et al.*, 2018; Glidden *et al.*, 2024)**.

Thus, the present work aimed to study the effects of meteorological data (annual atmospheric temperature) on total live freshwater snail counts in six Egyptian Delta governorates (Kafr El-Sheikh, Damietta, Menoufia, Gharbia, Dakahlia, and Beheira). Field data and water physical characteristics were used. CART analysis was applied to construct an optimal tree diagram, identifying the relative importance of meteorological variables (maximum and minimum air temperature) in explaining variations in snail abundance and water characteristics.

MATERIALS AND METHODS

Study area

Northern Egypt (Lower Egypt or the Nile Delta) is one of the world's largest river deltas. It is formed by the Nile River, which spreads out and drains into the Mediterranean Sea, lying between latitudes 30°00′ and 31°45′ N and longitudes 29°30′ and 32°30′ E. The Delta extends along 240 kilometers of Mediterranean coastline, from Alexandria in the west to Port Said in the east, and reaches approximately 160 kilometers in length from north to south.

This study was conducted at 41 sites across different watercourses, selected with the assistance of the Ministry of Health and Population (MOHP) in six Delta governorates: Kafr El-Sheikh, Damietta, Menoufia, Gharbia, Dakahlia, and Beheira **(Ismail *et al.*, 2023)**. Sampling was carried out across four successive seasons, with two visits per season during 2019–2020 (Fig. 1 & Table 1).

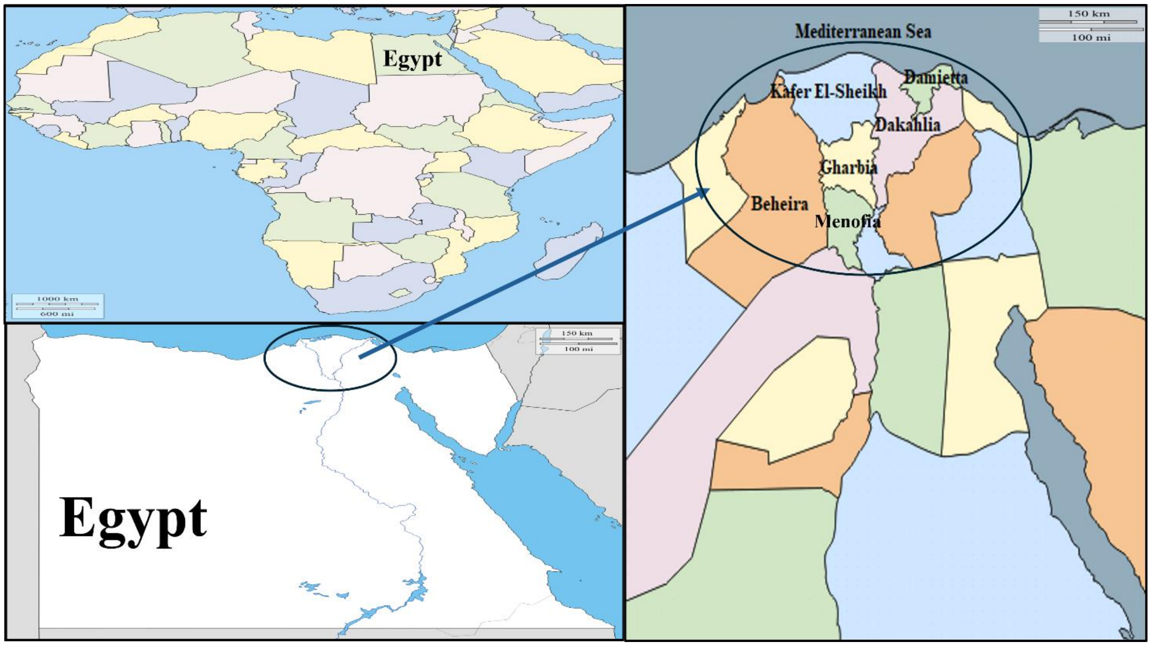

Fig. 1. Map of the study area showing the selective Egyptian governorates

Malacological survey

A seasonal survey of water banks was conducted at the selected sites across four successive seasons, from summer 2019 to spring 2020. Snail samples were collected, and ecological conditions were recorded on specially designed field sheets for each water body under study. At each site, snails were collected using a 500µm mesh standard dip net with five consecutive strikes covering several points along the bank **(Yousif *et al.*, 1992; Ibrahim *et al.*, 2005)**. The collected snails were placed in numbered plastic aquaria, transferred to the laboratory, sorted, identified, and counted. In addition, they were examined for natural infection **(Yousif *et et al.*, 1998; Ibrahim *et al.*, 1999; Ismail, 2009)**.

The physicochemical parameters of water at the selected Delta governorates had been previously measured in the study of **Ismail *et al.* (2023)**, which was conducted at the same sites. In the present survey, water temperature and hydrogen ion concentration (pH) were measured using a portable pH meter [Hanna Instruments, HI 9024]. Electrical conductivity (EC) and total dissolved solids (TDS) were measured with a portable conductivity meter (HI 9635), while dissolved oxygen (DO) was measured with a portable DO meter [Hanna Instruments, HI 98193]. All parameters were measured *in situ* at midday, 20 cm below the water's surface **(Jannat *et al.*, 2019)**. Moreover, they were recorded on field survey sheets following the standard methods outlined by **APHA (1998)**.

Table 1. Geographical characteristics and different water courses of the studied Delta governorates

Governorates	Geographical location	Characteristics	Sites	Centers	Villages
Kafr El- Sheikh	Coastal governorate, in the far North of Egypt, bordered by Rosetta branch in the West that stretches by 85 km till its mouth in the Mediterranean Sea, and by the Mediterranean Sea in the North.	Dry throughout the year. January is the wettest and coldest month with a maximum temperature of 20°C, August is the driest month with a maximum temperature of 35°C, and June is the sunniest month.	**9 sites in 6 villages in 2 centers**	**Qillin**	Minyat Qillin
					Al-Monshaah
					Al-Sughra
					Minshilayn
				Sidi-Ghazy	Om-Gaafar
					Saqr
Damietta	Coastal governorate in the northern part of Egypt in the Nile Delta. Surrounded by the Mediterranean Sea in the north and Manzala Lake in the east.	The climate is hot, dry in the summer, and mild rainy in the winter	**7 sites in 5 villages in 2 centers**	**Kafr Saad**	3 villages
				Kafr Al-Bateekh	Al-Read
					Om-Reda
Menoufia	Located in the Nile Delta, in northern Egypt, and to the south of Gharbia Governorate and north Cairo.	Dry throughout the year. The warmest month in Menoufia is August with an average maximum temperature of 36°C. January is the coldest month, featuring an average daytime maximum temperature of 21°C.	**8 sites in 8 villages in 3 centers**	**Ashmon**	Rosetta branch
					Abo-Elawally
					El-Noqrasheia
					El-Nagar ponds in Gress village
				Shibin Al-Kom	Al-Maslk
					Al-zeraa ponds
				Monouf	Shbsher tamaly
					Zawia Razen Dbrokee
Gharbia	Located in the north of the country, south of Kafr El Sheikh Governorate, and north of Menoufia Governorate.	Despite being located near the Nile, Gharbia generally has a very hot desert climate.	**4 sites in 4 villages in 2 centers**	**El-Mahalla El- Kubra**	Ayaash village
					El-kassed pond
					Branch of Showper Sea.
				Tanta	Meet Habesh (Ezbet Al-Sapeel)
Dakahlia	Dakahlia Governorate is considered the base of the Nile Delta. Located in the northeastern part of Egypt. It is bounded by Sharkia Governorate on the east, Gharbia and Kafr el-Sheikh Governorates on the west, the Mediterranean Sea on the north, Damietta on the northeast, and Qalyobia on the south.	Mild climate tends to be warm in winter with some rain that increases on the coasts, and hot in summer. average annual temperatures range from 14-28°C	**5 sites in 5 villages in 2 centers**	**Al-Mansoura**	Al-Mansoura
				Mit Ghamr	Ezbet belgay
					Meet Al- Akrrad
					Kom EL-Derrbi
					Al Maasara WA Kofoureha
Beheira	Coastal governorate in norther Egypt in the Nile Delta. Bordered by the Mediterranean Sea in the North and by the Rosetta branch in the East.	The annual air temperature varies from7°C to 35°C and is rarely below 4°C or above 39°C.	**8 sites in 7 villages in 2 centers**	**Shobra**	Ezbet Israf
					Ezbet Beshara
				Damanhour	Damatuoh
					Alwusta
					Zarkon
					Hassan Khair
					Iflaka

According to a previous study by the same authors **(Ismail *et al.*, 2023)**, physicochemical parameters varied across the examined sites in all included governorates. Water temperature was significantly correlated with the annual maximum (Tmax) and minimum (Tmin) atmospheric temperatures in the selected years. In contrast, EC, TDS, DO, and pH were inversely correlated with Tmax and water temperature. In addition, DO showed an inverse correlation with Tmin. EC and TDS were significantly correlated with each other, and both were also correlated with Tmin. Similarly, pH exhibited a negative correlation with Tmax and water temperature, while showing significant correlations with other water quality parameters (EC, TDS, and DO).

Meteorological data

Ground-based monitoring stations

In this study, daily meteorological temperature data were obtained from ground-based monitoring stations operated by the Egyptian Meteorological Authority (EMA). The selected stations—Al-Mansoura, Tanta, Quessna, Sakh, Damietta, and Rashid—were chosen because they cover the study areas, with each station representing a 50km diameter region. Data were collected for the past 10 years (2006–2015) and for the study period (2019–2020), as available in the EMA electronic database. Climate data were analyzed to extract extreme weather indicators, particularly extreme air temperatures. The relationships between these climate extremes and freshwater snail data were examined to determine potential links **(Yimiao *et al.*, 2024)**.

Statistical methodology

Statistical analyses were conducted using Minitab version 20.1.3. Quantitative data were expressed as mean ± standard deviation (SD). Correlation coefficients were calculated to assess the relationships between total live snail counts and meteorological variables. Minitab was also used to determine the relative importance (%) of predictor variables for live snail abundance.

Classification and Regression Tree (CART) analysis was applied to explore the data and to classify ecological systems influenced by natural factors. CART was further used to identify the relative importance of meteorological factors in differentiating homogeneous groups within the dataset of total live snail counts.

RESULTS

Malacological survey

In the present study, the field survey revealed a total of 3,227, 3,813, 5,736, and 3,533 live snails, along with 19 bivalves, collected from different sites across the six selected governorates during summer, autumn, winter, and spring of 2019–2020, respectively. The percentage distribution of all collected freshwater snails from each governorate across the four seasons is shown in Fig. (2).

During summer, autumn, and winter, the highest proportions of live snails were recorded in Beheira (44.7%, 34.5%, and 48.9%, respectively), followed by Kafr El-Sheikh (25.5%, 29.6%, and 20.3%, respectively). In contrast, during spring the highest proportion was recorded in Damietta (29%).

Seasonal patterns varied among governorates. In Beheira, snail abundance followed the trend winter > summer > autumn, whereas in Kafr El-Sheikh it followed winter > summer > autumn. In Damietta, the highest abundance occurred in spring, with considerably lower percentages observed during the other seasons (Fig. 2).

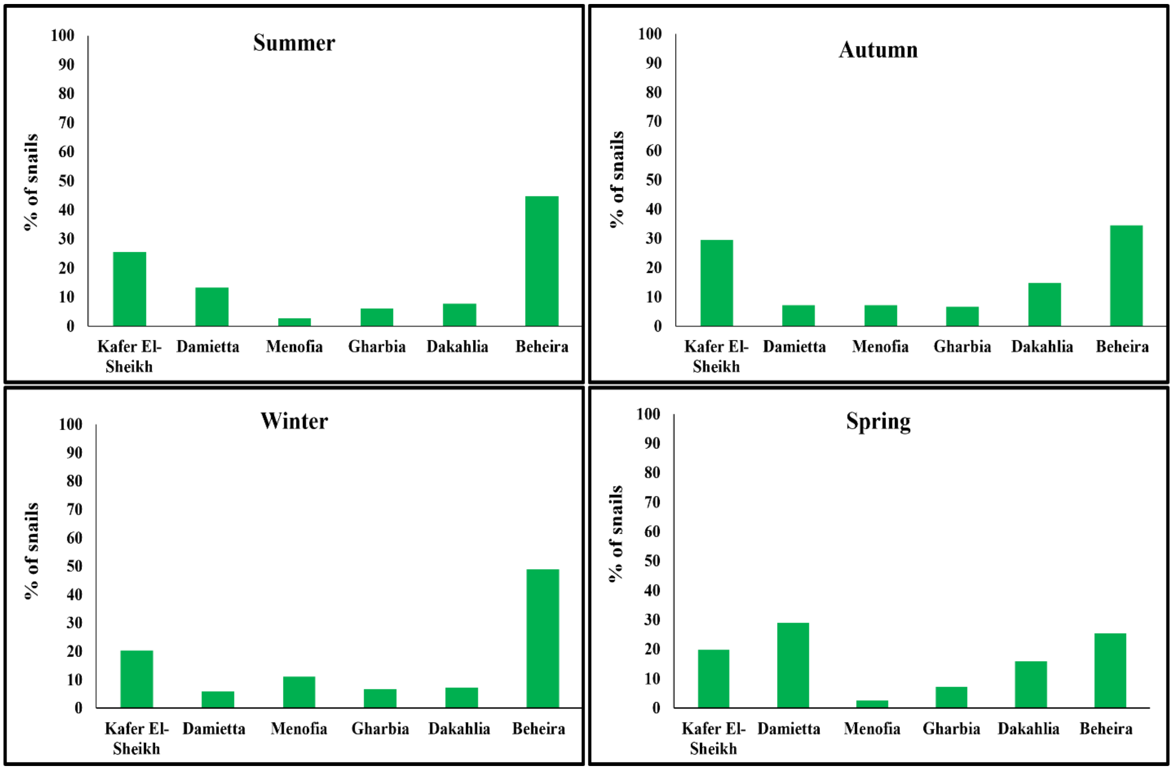

Fig. 2. Percentage of the collected freshwater snail species from different selected governorates during different seasons (2019-2020)

Physicochemical parameters

The present study indicated that the total live freshwater snails collected from the six examined Delta governorates were significantly and inversely correlated with maximum atmospheric temperature (Tmax) and water temperature during both the past decade (2006–2016) and the current study period (2019–2020), as shown in Table (2). In contrast, snail abundance was positively correlated with other physicochemical water parameters, including EC, TDS, DO, and pH.

Water temperature itself was significantly correlated with both annual Tmax and minimum atmospheric temperature (Tmin) in the selected years. Meanwhile, EC, TDS, DO, and pH were significantly and inversely correlated with Tmax and water temperature. In addition, DO was inversely correlated with Tmin. EC and TDS were significantly correlated with Tmin, while pH showed significant negative correlations with both Tmax and water temperature.

Table 2. Relationships between the total live snail count and physical characters of water with the annual atmospheric temperatures (2006-2020)

	Total Live snails count		Tmax		Tmin		Temperature C°		EC (µcm)		TDS (ppm)		DO (mg/L)	
	r=	P-Value	r=	P-Value	r=	P-Value	r=	P-Value	r=	P-Value	r=	P-Value	r=	P-Value
Tmax	-0.3	0.000												
Tmin	-0.1	0.249	0.8	0.000										
Temperature C°	-0.2	0.000	0.5	0.000	0.4	0.000								
EC (µcm)	0.6	0.000	-0.1	0.01	0.2	0.000	-0.2	0.001						
TDS (ppm)	0.6	0.000	-0.1	0.01	0.2	0.000	-0.1	0.005	0.9	0.000				
DO (mg/L)	0.2	0.01	-0.7	0.000	-0.7	0.000	-0.5	0.000	0.01	0.859	0.05	0.300		
pH	0.7	0.000	-0.2	0.000	-0.01	0.922	-0.4	0.000	0.5	0.000	0.4	0.000	0.1	0.01

Tmax: maximum atmospheric temperatures; Tmin: minimum atmospheric temperature; EC.: Electric Conductivity; TDS: Total Dissolved solids; DO: Dissolved Oxygen, pH: Hydrogen ion concentration.

In the present study, Classification and Regression Tree (CART) analysis was used to identify predictor variables for the abundance of total live snails in the six examined governorates. The relative importance of predictor variables was calculated, and optimal tree diagrams were generated for each governorate.

Kafr El-Sheikh Governorate

The most important predictors were pH and water temperature (100% importance), followed by EC and TDS (61.2%) (Fig. 3a). The optimal tree diagram (Fig. 3c) showed two main modules based on water temperature. When water temperature was ≤ 22.25°C, Tmax further divided the data into two submodules: Tmax ≤ 24.6°C (23.5% of data) and Tmax > 24.6°C (20.6%). When water temperature was > 22.25°C, the split was based on Tmin: Tmin ≤ 17.5°C (29.4% of data) and Tmin > 17.5°C (26.5%). The most predictive condition was water temperature > 22.25°C combined with Tmin ≤ 17.5°C.

Damietta Governorate

The most important predictors were pH, EC, and TDS (100% importance). Water temperature, DO, and Tmax had 75.8% importance, while Tmin had 59.3% (Fig. 3b). The optimal tree diagram (Fig. 3d) showed two main modules based on EC. When EC was ≤ 1646.5 µS/cm, Tmax divided the data into two submodules: Tmax ≤ 26.7°C (39% of data) and Tmax > 26.7°C (8.7%). When EC was > 1646.5 µS/cm, Tmax was again the divider: Tmax ≤ 25.2°C (34.8% of data) and Tmax > 25.2°C (17.4%). The most predictive condition was EC ≤ 1646.5 µS/cm and Tmax ≤ 26.7°C.

Menoufia Governorate

The most important predictors were DO and water temperature (100% importance), followed by Tmax and Tmin (>90% importance) (Fig. 4a). The optimal tree diagram (Fig. 4c) showed four modules. When Tmax ≤ 22.75°C, 21% of the data were explained. When Tmax > 22.75°C, water temperature determined the submodules: water temperature ≤ 23.3°C (25%), water temperature > 23.3°C with Tmax ≤ 30.95°C (35.7%), and water temperature > 23.3°C with Tmax > 30.95°C (17.9%). The most predictive condition was Tmax between 22.75°C and 30.95°C with water temperature > 23.3°C.

Gharbia Governorate

The most important predictors were Tmax and water temperature (100%), followed by EC and TDS (82%) and Tmin (68.9%) (Fig. 4b). The optimal tree diagram (Fig. 4d) produced four modules. When Tmax ≤ 22.25°C, 18.2% of the data were explained. When Tmax > 22.25°C, three modules of nearly equal importance (27.3% each) were identified: Tmax between 22.25°C–27.7°C, between 27.7°C–31.5°C, and > 31.5°C.

Dakahlia Governorate

The most important predictors were Tmax, Tmin, DO, EC, TDS, and pH (all 100%). Water temperature showed relatively lower importance (36.4%) (Fig. 5a).

Beheira Governorate

The most important predictors were Tmax, Tmin, EC, and water temperature (all 100%). TDS also had high importance (93.4%) (Fig. 5b). This finding was consistent with the correlations presented in Table (2), where water temperature was significantly associated with both Tmax and Tmin.

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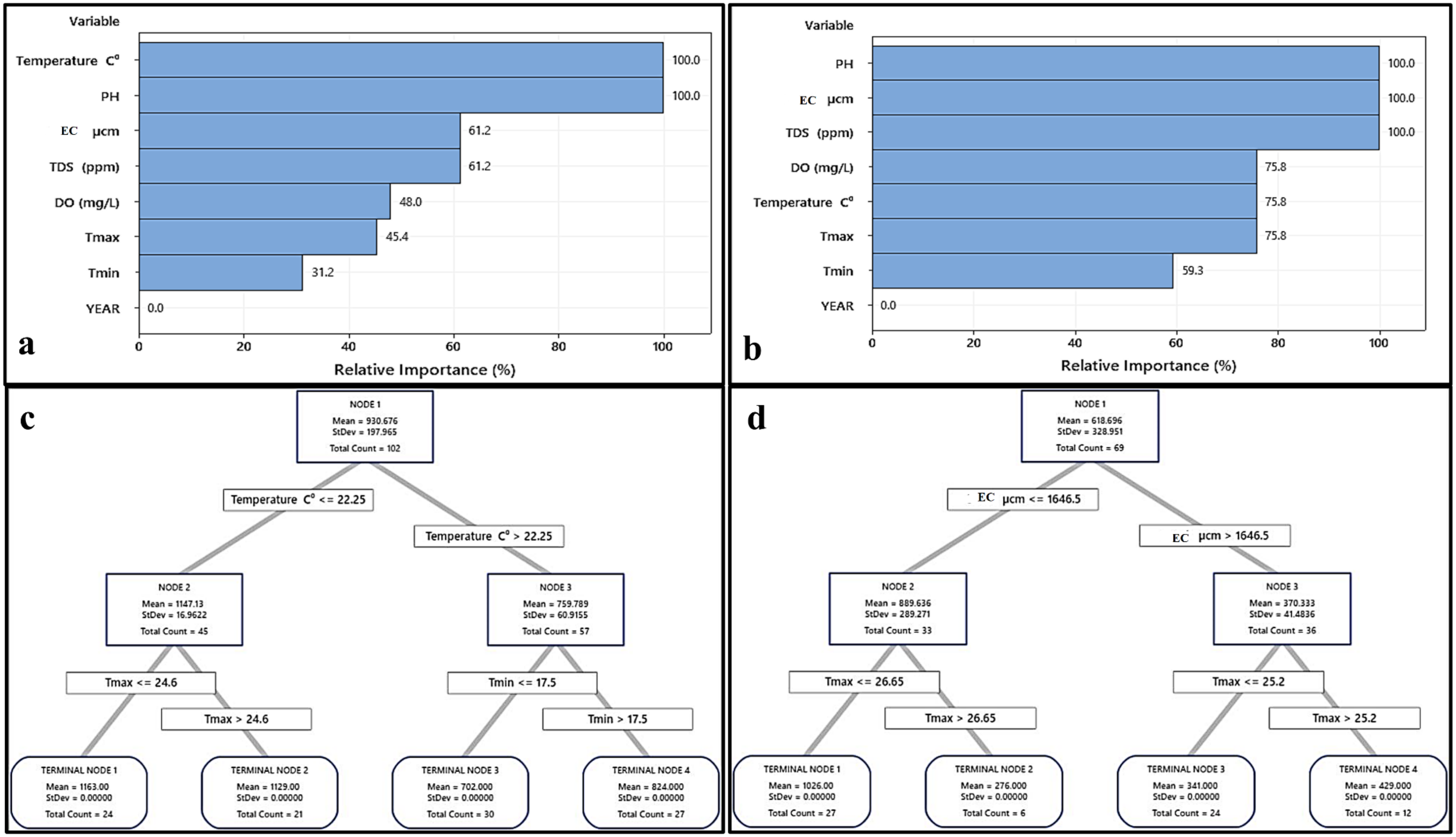

Fig. 3. Relative importance percent of the predictors effect for the count of total live snails in Kafr El-Sheikh (**a**) and Damietta (**b**) Governorates, Optimal Tree Diagram of CART regression chart of the significant predictors for total live snails in Kafr El-Sheikh (**c**) and Damietta (**d**) Governorates

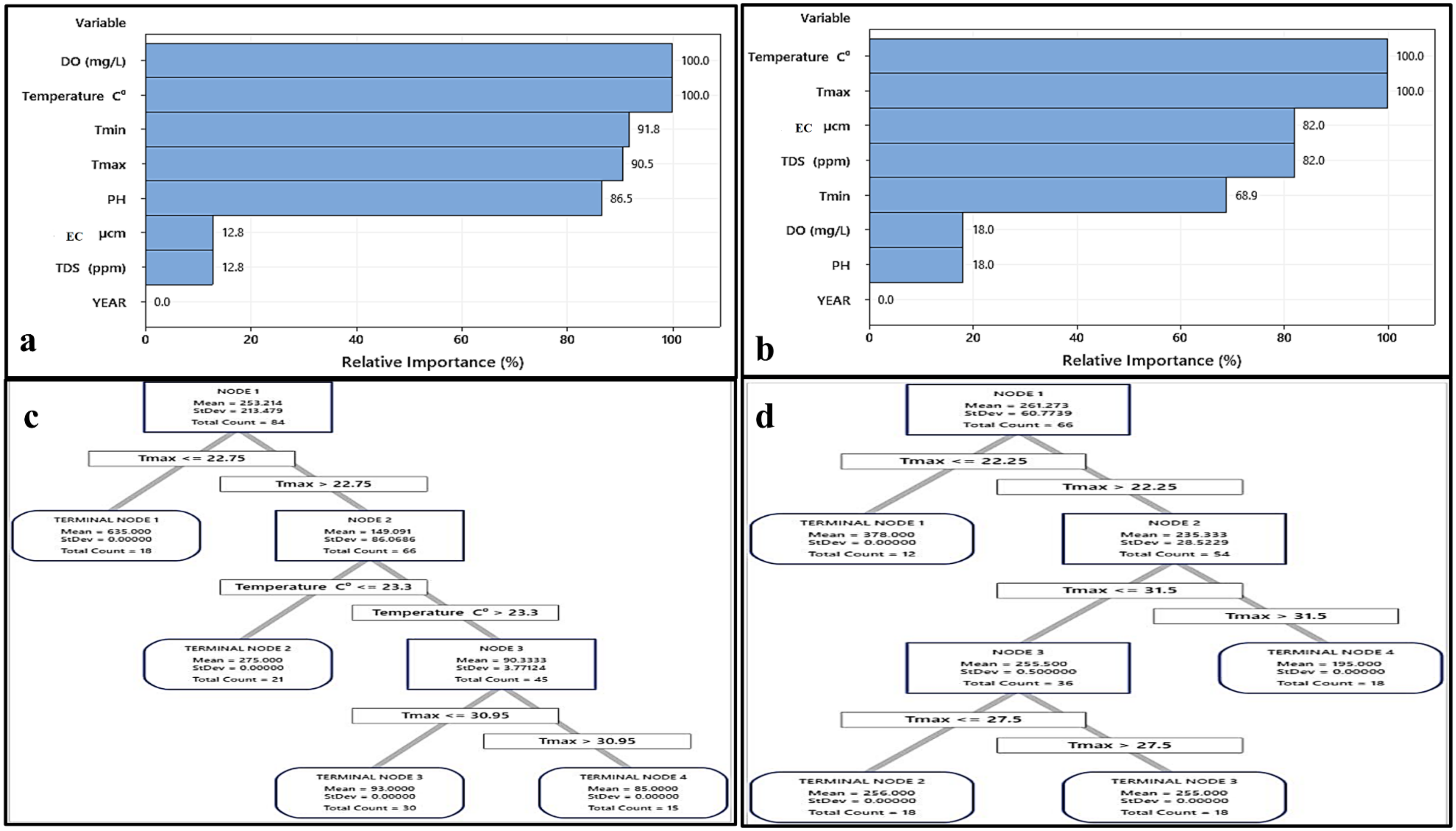

Fig. 4. Relative importance percent of the predictors effect for the count of total live snails in Menoufia (**a**) and Gharbia (**b**) Governorates, Optimal Tree Diagram of CART regression chart of the significant predictors for total live snails in Menoufia (**c**) and Gharbia (**d**) Governorates

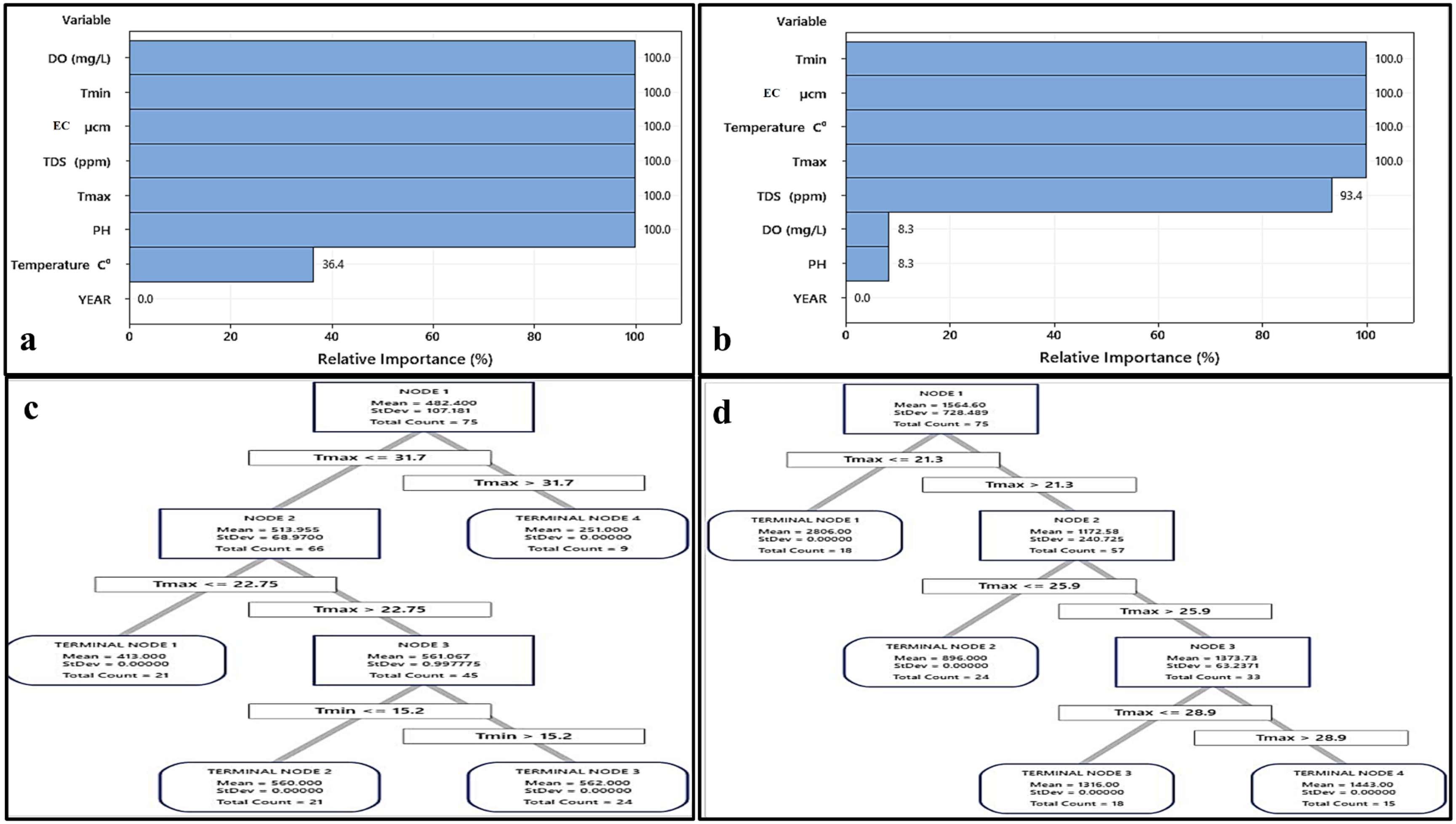

Fig. 5. Relative importance percent of the predictors effect for the count of total live snails in Dakahlia (**a**) and Beheira (**b**) Governorates, Optimal Tree Diagram of CART regression chart of the significant predictors for total live snails in Dakahlia (**c**) and Beheira (**d**) Governorates

The optimal tree diagram (Fig. 5c) using CART regression analysis for Dakahlia Governorate produced four modules (terminal nodes). The first was based on annual Tmax > 31.7°C, which explained 12% of the data. When Tmax ≤ 31.7°C, three additional modules were identified: Tmax ≤ 22.75°C (28%), Tmax > 22.75°C with Tmin ≤ 15.2°C (28%), and Tmax > 22.75°C with Tmin > 15.2°C (32%). The most predictive condition was Tmax > 22.75°C combined with Tmin > 15.2°C.

The optimal tree diagram (Fig. 5d) for Beheira Governorate also yielded four modules. The first was based on Tmax ≤ 21.3°C, which explained 24% of the data. When Tmax > 21.3°C, three further modules were identified: Tmax ≤ 25.9°C (32%), Tmax > 25.9°C with Tmax ≤ 28.9°C (24%), and Tmax > 28.9°C (20%). The most predictive condition was Tmax between 21.3°C and 25.9°C.

A summary of predictor importance across governorates is presented in Table (3), while the most effective predictor modules derived from CART regression are shown in Table (4). These results indicate variation in the relative importance of predictors among governorates. Nevertheless, CART analysis identified the most influential modules for predicting live snail counts in each region.

Overall, Tmax emerged as the most important predictor in five governorates (Damietta, Menoufia, Gharbia, Dakahlia, and Beheira), while Tmin was most influential in two governorates (Kafr El-Sheikh and Dakahlia). Water temperature was considered 100% important in Kafr El-Sheikh and Menoufia, whereas conductivity, together with Tmax, were the only two variables with 100% importance in Damietta.

These findings suggest that changes in atmospheric temperature, as a consequence of global warming, may alter the occurrence and abundance of freshwater snail species in the Nile Delta.

Table 3. Importance percent of the different predictors in Delta governorates

Variable	Governorates					
	Kafr El-Sheikh	Demietta	Menoufia	Gharbia	Dakahlia	Beheira
Tmax	-	+	++	+++	+++	+++
Tmin	-	+	++	+	+++	+++
Water temperature ºC	+++	+	+++	+++	-	+++
EC (µcm)	+	+++	-	++	+++	+++
TDS (ppm)	+	+++	-	++	+++	++
DO (mg/L)	-	++	+++	-	+++	-
pH	+++	+++	++	-	+++	-

N.B: (+++) =100%, (++) = >80%-< 100%, (+) = <80% - >50%, (-) = < 50%. Tmax: maximum atmospheric temperatures; Tmin: minimum atmospheric temperature; EC: Electric Conductivity; TDS: Total Dissolved solids; DO: Dissolved Oxygen, pH: Hydrogen ion concentration.

Table 4. The most predictor modules in the different Delta governorates according to the CART regression chart

Variable	Governorates					
	Kafr El-Sheikh	Demietta	Menoufia	Gharbia	Dakahlia	Beheira
Tmax	-	+++	+++	+++	+++	+++
Tmin	+++	-	-	-	+++	-
Water temperature ⁰C	+++	-	+++	-	-	-
EC (µcm)	-	+++	-	-	-	-
TDS (ppm)	-	-	-	-	-	-
DO (mg/L)	-	-	-	-	-	-
PH	-	-	-	-	-	-

N.B: (+++) =100%, (++) = >80%-< 100%, (+) = <80% - >50%, (-) = < 50%. Tmax: maximum atmospheric temperatures; Tmin: minimum atmospheric temperature; EC.: Electric Conductivity; TDS: Total Dissolved solids; DO: Dissolved Oxygen, pH: Hydrogen ion concentration.

DISCUSSION

Freshwater snails (Phylum: Mollusca, Class: Gastropoda) are distributed across freshwater ecosystems throughout Egypt. Numerous studies have focused on freshwater mollusks in the Nile River and its canals, particularly the medically important snail species capable of transmitting diseases to humans and livestock. These snails serve as essential intermediate hosts for trematodes, which underscores their medical importance **(Pokora, 2001; El-Hommossany, 2006; El-Khayat *et al.*, 2011, 2017)**. The distribution, seasonal abundance, and population dynamics of freshwater snails depend on the physical geography of a given region and are strongly influenced by physical, chemical, and biological parameters, as well as climatic factors **(El-Khayat *et al.*, 2011; El-Khayat *et al.*, 2013; Koudenoukpo *et al.*, 2021; Min *et al.*, 2022; Ayob *et al.*, 2025)**.

The present field survey revealed that snail abundance varied among governorates and seasons. In Beheira, the pattern followed winter > summer > autumn. In Kafr El-Sheikh, the trend was winter > summer > autumn, while in Damietta, the highest percentages were observed in spring, with very low percentages in other seasons. These findings are consistent with earlier studies by **El-Khayat *et al.* (2011)**, who recorded 13 freshwater snail species across seven governorates (The Nile River, branches, and canals) in a two-year survey. Similarly, **Min *et al.* (2022)** reported that the predominant species in China were *Sinotaia quadrata*, *Biomphalaria straminea*, and *Physa acuta*.

Correlation analyses indicated that total live snail counts in the six examined Delta governorates were significantly and inversely correlated with Tmax and water temperature (2006–2016 and 2019–2020). Conversely, snail counts were positively correlated with EC, TDS, DO, and pH. Water temperature was significantly correlated with both Tmax and Tmin, while EC, TDS, DO, and pH were inversely correlated with

Tmax and water temperature. Additionally, DO was inversely correlated with Tmin; EC and TDS were significantly correlated with Tmin; and pH was negatively correlated with both Tmax and water temperature. These results are supported by the findings of **Njoku-Tony (2011)**, **Yirenya-Tawiah *et al.* (2011)**, **Rowel *et al.* (2015)**, **Getachew *et al.* (2018)** and **Adekiya *et al.* (2020)**.

For example, **Yirenya-Tawiah *et al.* (2011)** reported that air temperatures of 27.4–33°C favored species such as *B. truncatus*, *B. globosus*, *B. pfeifferi*, *Melanoides* spp., *Physa waterlotti*, and *Pila* sp. **Njoku-Tony (2011)** found that freshwater snails tolerated 23–33°C and observed that conductivity below 50 µmhos coincided with reduced abundance. In Uganda, **Rowel *et al.* (2015)** showed that pH and conductivity influenced *Biomphalaria* populations, while in Ethiopia, **Getachew *et al.* (2018)** identified pH, conductivity, BOD_5, and DO as key determinants of snail occurrence. Similarly, **Adekiya *et al.* (2020)** linked conductivity and pH to climate change effects on schistosomiasis transmission in SSA.

In Egypt, **El-Deeb *et al.* (2017)** reported that snail density decreased sharply above 34°C in Giza and Kafr El-Sheikh. They also found *B. alexandrina* within TDS ranges of 120–901 mg/L and DO levels of 2.65–2.71 mg/L. Using correspondence analysis, **El-Khayat *et al.* (2017)** showed that snail abundance was strongly associated with temperature, pH, conductivity, and DO (explaining 91.8–95.4% of variance). Likewise, **Marie *et al.* (2015)** found snails across a wide pH range (7.6–8.5) in Egypt, while **Ntonifor and Ajayi (2007)** reported ranges of 7.2–10.9 in Nigeria. However, extreme fluctuations in pH (<7.0 or >9.0) reduced snail abundance to <15% **(Marie *et al.*, 2015)**. Notably, *B. alexandrina* exhibited greater tolerance to environmental variability than other species **(Kazibwe *et al.*, 2006; El-Khayat *et al.*, 2009; Marie *et al.*, 2015)**. Beyond freshwater systems, climate-driven CO_2 release has also been shown to reduce ocean pH by 0.28–0.7 units, leading to acidification **(Caldeira & Wickett, 2003)**.

CART analysis further demonstrated that Tmax was the most important predictor of snail distribution in five governorates (Damietta, Menoufia, Gharbia, Dakahlia, and Beheira), while Tmin was most influential in Kafr El-Sheikh and Dakahlia. Conductivity, together with Tmax, were the only two variables with 100% importance in Damietta. These results are consistent with **Min *et al.* (2022)**, who used decision tree models and CCA in China and identified physical habitat characteristics, water quality, and biotic factors as key drivers of snail abundance. They also align with findings by **Nkolokosa *et al.* (2023)** in Malawi, who used Random Forest models to predict *B. pfeifferi* distribution, highlighting conductivity, TDS, elevation, and water temperature as critical factors. Similarly, **Koudenoukpo *et al.* (2021)** employed multivariate modeling in Benin and showed that mollusk assemblages were structured by physicochemical variables along a river–estuary continuum. In Ethiopia, **Getachew *et al.* (2018)** applied decision tree and multivariate analyses, identifying canopy cover, water body type, waste disposal, and pH as key predictors of snail occurrence.

CONCLUSION

In the six Delta governorates, physicochemical characteristics of water—such as temperature, EC, TDS, DO, and pH—together with annual atmospheric temperatures (Tmax and Tmin), were identified as crucial factors in predicting the occurrence and abundance of freshwater snails. To assess climatic risk factors influencing snail survival, CART analysis was applied. The results indicate that global warming–induced changes in atmospheric temperature may alter both the presence and abundance of freshwater snails within their habitats. Consequently, atmospheric temperature should be regarded as a key determinant that significantly shapes the diversity of freshwater snail populations, including those of medical importance as disease vectors.

FUNDING

This work was supported by Theodor Bilharz Research Institute (TBRI), Egypt (Grant No.106C).

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design, data collection, and analysis. Sample collection was performed by **Suzan E. Ali, Nahed M.M. Ismail,** and **Asmaa Abdel-Motleb.** Statistical analysis and use of the optimal tree diagram using CART analysis were done by **Amal Saad-Hussein and Naglaa Zanaty.** The first manuscript draft was written by **Nahed M.M. Ismail** and **Asmaa Abdel-Motleb** reviewed and commented on the previous version of the manuscript. All authors read and approved of the final manuscript. The authors have no relevant financial or non-financial interests to disclose.

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ARABIC SUMMARY

سيناريوهات تغير المناخ للتنبؤ بقواقع المياه العذبة باستخدام شجرة التصنيف والانحدار (CART): محافظات الدلتا المصرية كدراسة حالة.

[1] أمل سعد حسين، [2] ناهد محمد إسماعيل، [3] نجلاء زناتى، [2] سوزان عز الدين على، [2]* أسماء عبد المطلب

[1] قسم الطب البيئي والمهني، معهد بحوث البيئة وتغير المناخ، المركز القومي للبحوث، الجيزة، مصر.
[2] قسم بحوث البيئة، معهد تيودور بلهارس للأبحاث، الجيزة، مصر.
[3] الهيئة القومية للاستشعار عن بُعد وعلوم الفضاء، القاهرة، مصر.

*** Corresponding author: a_abdelmotlb@yahoo.com**

الاحتباس الحراري الناجم عن تغيّر المناخ قد يُغيّر خصائص المياه العذبة. فارتفاع درجات حرارة المياه يؤدي إلى زيادة التبخر وانخفاض تركيز الأكسجين، مما قد يؤثر على بقاء وتكاثر قواقع البطنقدميات التى تعيش فى المياه العذبة. لذا، هدفت هذة الدراسة إلى التنبؤ بوجود ووفرة قواقع المياه العذبة في ست محافظات من محافظات الدلتا (كفر الشيخ، دمياط، المنوفية، الغربية، الدقهلية، والبحيرة) خلال السنوات المختارة (2010-2016 والمسح الحالي 2019-2020) باستخدام المعايير الفيزيائية والكيميائية للمياه مثل درجة الحرارة، والتوصيل الكهربائي(EC) ، والمواد الصلبة الذائبة الكلية (TDS) ، والأكسجين الذائب (DO) ، وتركيز أيونات الهيدروجين(pH) ، بالإضافة إلى كل من الحد الأقصى السنوي (Tmax) والحد الأدنى السنوي (Tmin) لدرجة الحرارة الجوية باستخدام شجرة التصنيف والانحدار(CART) . كشف المسح الميداني أن أعلى نسب لأنواع القواقع الحية التي تم تجميعها سجلت في البحيرة (48.9٪، 44.7٪، و34.5٪، خلال فصل الشتاء والصيف والخريف على التوالي) ودمياط خلال فصل الربيع (29٪). ووفقًا لتحليلCART ، كان Tmax هو المتغير الأكثر أهمية الذي يؤثر على حدوث وتوزيع أنواع القواقع في خمس محافظات (دمياط والمنوفية والغربية والدقهلية والبحيرة) و Tmin في محافظتين (كفر الشيخ والدقهلية). وبالمقارنة، كانت EC مع Tmax المتغيرين الوحيدين اللذين كانا مهمين بنسبة 100٪ في دمياط. وبالتالي، فإن تغير درجة الحرارة الجوية بسبب الاحتباس الحراري قد يغير من وجود وتوزيع القواقع في المياه العذبة في مواطنها. لذلك، تعتبر درجة الحرارة الجوية عاملاً محددًا ويلعب دورًا مهمًا في تنوع وتوزيع القواقع في المياه العذبة الناقلة للأمراض.