

Tolerance of Benthic Diatoms to Severe Environmental Stress: A Case Study in Shatt Al-Arab River, Basrah, Iraq

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Abstract: The present work aims at investigating the ability of diatoms to re-establish their community after a severe environmental stress such as desiccation. Diatoms were subjected to extreme environmental stress to observe their survival capability. Samples of sediment were collected from three sites, Maqal, Abu Flos and Al-Faw along the course of Shatt Al-Arab river. Different temperature regimes were implemented for testing the ability of diatoms to recover from desiccation. Experiments were performed at various temperatures, 10, 15, 20, 25, 30, 35 and 40 °C. A total of 67 diatom species were identified and included freshwater forms (25%), brackish water forms (25%) and marine species (26%), as well as 24% of taxa with undefined ecological preferences. The recovery rate of diatom species at all sites appeared to be rather similar. 40%, 38% and 37% of all taxa encountered were able to recover from desiccation at sites 1, 2 and 3, respectively. Recovering ability of those species varies with variable temperature. Favourable temperature for most species to regrow ranged between 15 and 25 °C. *Nitzschia palea* exhibited the maximum growth rate at all temperatures (10-35 °C). 32% of all epiphytic species encountered were able to recover at 20 °C. Five species: *Craspedostauros britannicus*, *Nitzschia invisitata*, *Pinnularia quadratarea*, *Simonsenia* sp. and *Tryblionella plana* were not previously reported in Iraq and considered as new to the region. A new species, *Synedropsis abuflosensis*, was found. The outcome of the present work clearly indicates that some species of diatoms can recover after exposure to severe environmental stress.

Keywords: Diatoms, Desiccation, Environmental stress, Shatt Al-Arab river, Temperature

Introduction

Diatoms are the dominant phytoplankton group that occur in all aquatic habitats; freshwater, brackish water, marine and some live on exposed wet soils (terrestrial) (Quiroga & Chretiennot-Dinet, 2004; Warkiewicz et al., 2018). They are very important components of the aquatic environment as they form "with other algae" the base of the trophic levels. Diatoms constitute a fundamental link between primary (autotrophic) and secondary (heterotrophic) production. Many microorganisms feed on diatoms and in this way, they are integrated into aquatic food webs (Mann et al., 2017). They are responsible for 20% to 25% of global

carbon fixation and 40% of primary production in all oceans and constitute the major source of atmospheric oxygen (Berger, 2007; Renaudie, 2016).

Diatoms are widely distributed from equator to poles, and inhabit various types of substrates (Round et al., 1990). They live either freely in the water column (planktonic diatoms) or spend most of their time living on the bottom (benthic diatoms). According to their living mode, benthic diatoms can be divided into two subgroups: motile benthic diatoms and attached benthic diatoms (Pinckney et al., 1994; Dickman et al., 2005).

Diatoms are usually more sensitive to environmental changes than other benthic microalgae (Schneider et al., 2012). Thus, they are commonly used throughout the world as bioindicators to monitor changes in water quality due to their specific tolerance to various environmental parameters: nutrient concentrations, pH, salinity, temperature, conductivity and organic pollution (Gale, 2016). One of the most influencing environmental parameters on diatom distribution, occurrence and growth is temperature, which is responsible for the appearance or disappearance of the different diatom species (Bopp et al., 2005).

Diatoms exist and thrive across many environments ranging from cold water to hot springs (Maguire et al., 2013). Some diatoms have a rather narrow temperature range outside which cells die (Anderson, 2000; Zhang et al., 2018). On the other hand, temperature affects diatoms more than any other environmental factor and this effect can be in one of two distinct ways: directly on metabolic rates and indirectly by its impact on nutrient availability and uptake (Lewandowska et al., 2014). Temperature plays significant role in diatoms primary production (Berges et al., 2002; Behrenfeld et al., 2006). Generally, productivity increase in lower temperature as a result of increasing activity of some enzymes associated with photosynthesis (Prelle et al., 2019).

In Southern Iraq, particularly in Basrah District, environmental conditions are becoming severe during the prolonged warm periods which lead to desiccation in several aquatic habitats such as the shallow ponds, marginal marshes and coastal areas of Shatt Al-Arab river. Even so, no attempt was made to study the ability of benthic microalgae to survive such conditions. The only few investigations made on the tolerance of diatoms to environmental conditions focused on the effect of various environmental parameters such as temperature on planktonic diatoms (Hussein et al., 2009; Al-Shawi et al., 2012). These authors studied the effect of thermal water discharged from electric power plants in Najebiya and Hartha sites on planktonic algae and merely provided list of species found in the area. On a very narrow scale, Al-Hassani et al. (2009) studied the optimum temperature and light intensity for the growth of *Nitzschia palea* in culture conditions.

The present study aims at investigating the ability of diatoms to recover after prolonged periods of high temperature and desiccation. It is the first study in the region to elaborate the survival rate of diatoms in harsh environmental conditions.

Material and Methods

Study Area

Shatt Al-Arab River (30° 18' N, 48° 53' E) flows through Basrah City in Southern Iraq and extends for approximately 204 km (Fig. 1). It originates by the confluence of the two major rivers in Iraq, Tigris and Euphrates, at Qurna City north of Basrah, flowing southwards to discharge into the Arabian Gulf. The river width ranges between 400 m around Basrah City to 1500 m further south at Faw Town, with a depth ranging from 7 to 14 m, depending on tidal cycle (Abdullah, 1990; Mohamed & Abood, 2017).

Ecological characters of the Shatt Al-Arab River are affected by the semi-diurnal tidal cycle of the Arabian Gulf. During high tide, water rises to ca 3 m at Faw City and ca 0.5 m around Basrah urban region (Al-Hassan & Hussain, 1985). Historically, Shatt Al-Arab River also receives water from two tributaries, Swaib and Karun rivers which flow in the Iranian territories. Swaib River receives water from Huwaiza Marsh and discharges into water impoundments to the southern parts of Qurna City. Karun River discharges into the southern part of Shatt Al-Arab river. Both tributaries, however, were diverted into the Iranian land and no longer supply water to Shatt Al-Arab River (Al-Hassan & Hussain, 1985).

Shatt Al-Arab River is the main waterway in Basrah and it is largely used for drinking, agriculture and transport. Parts of the river, close to crowded populations, suffers from high level of pollution, both organic and inorganic. In many places, untreated domestic and industrial outflows find their way to the river, causing various environmental stresses, which affect both human and aquatic life (Naff & Hanna, 2003; Mohamed & Abood, 2017).

Sampling and Preparations

Sampling was carried out During July and August 2020 at three sites along the shoreline of Shatt Al-Arab River (Fig. 1). Site 1 is located at Maqal area (30° 34' 39'' N, 47° 46' 45'' E), about 8.1 km to north of Basrah City center, opposite to Al-Maqal port. Site 2 was at Abu Flos village (30° 27' 08'' N, 48° 01' 59'' E), located opposite to Abu Flos port, 25 km south of Basrah City Center and 45 km to site 1. Site 3 was selected at Al-Faw City (29° 58' 22'' N, 48° 28' 14'' E) to represent highly brackish water habitat.

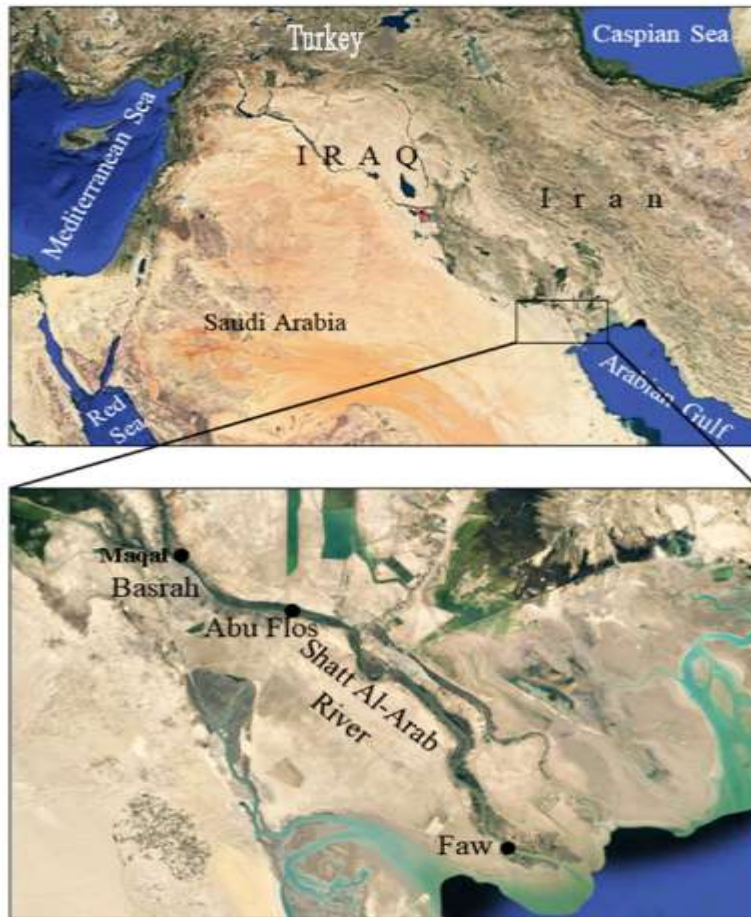


Figure 1: Map showing study area and location of sampling sites (black circles).

Diatoms Collection

Epipelagic diatoms were collected by scraping the uppermost 0.5 cm of sediment from randomly selected spots at each site, following the technique described by Eaton & Moss (1966). All samples were mixed and kept in large containers. Upon return to the laboratory, sediment samples were remixed carefully and transferred into plastic Petri dishes (9 cm diameter) with 1 cm depth. Except for the cover, all Petri dishes were wrapped with aluminum foil to prevent light from penetrating to the sediment and forcing diatom cells to migrate upwards. For each site, 100 Petri dishes were used for various analysis. Small portions of the sediment were directly treated for identification of natural diatom flora (see below).

Water Samples

From each site, water samples were collected in 10 L plastic containers for culture experiments. In the laboratory, the water was filtered through GF/C filter to eliminate any organic or suspended material and then left at room temperature.

Environmental Parameters

In situ air and water temperature were measured by using ordinary mercury thermometer. Salinity was measured by using portable conductivity meter model Cond 3110 set 1 (WTW- Germany) and a portable pH meter model pH 3110 set 2 (WTW- Germany) was used to measure the hydrogen ion concentration.

Experimental Design

For testing the ability of diatoms to recover desiccation under different temperature regimes, Petri dishes from all sites (50 Petri dish for each site) were allowed to completely dry at 48-50 °C ambient temperature, away from dust, and kept for four weeks. Prior to the experiment, four Petri dishes and one liter of filtered natural water from each site were left in the incubator at a particular temperature for 24 hours. This is necessary that dry samples and water have the same temperature specified for the experiment. In the next day, dry samples were covered with the filtered natural water and allowed to acclimatize for 24 hours in the incubator. In order to collect only benthic diatoms that have recovered, a microscope slide or lens tissue were placed on the sediment in each Petri dish. Slides were inspected for growing diatoms every 72 hours for 14 days for each experiment.

For inspecting the preferred temperature for diatoms to recover, experiments were performed at 10, 15, 20, 25, 30, 35 and 40°C. This range of temperature values was selected to mimic the expected temperature fluctuations in the study area during different periods of the year. The effect of each temperature treatment was tested by incubating four replicates of dry sediment for each site in an incubator equipped with cool-white fluorescent tubes at a 16:8-h light: dark cycles. Filtered natural water was added to Petri dishes when necessary to keep sediment samples wet during the course of the experiments. No culture media or other nourishments were incorporated in order to only simulate natural nutrient resources. Growth of diatoms was monitored every 72 hours. This was carried out by removing the slides from the sediment and growing diatoms were completely scrapped in small vials.

Scrapped samples were fixed with 70% ethanol until the time of further treatment. Diatoms in the vials were later cleaned and permanent slides were made for species identification and relative abundance estimation. Inspection of diatoms recovery was made for five times (every 72 hours) during every temperature experiment which lasted for two weeks. The period of two weeks was initially determined after a poilet experiment for growing dry diatoms which showed that no new growth was appeared after a two weeks incubation period.

Diatom Cleaning and Examination

Diatom frustules were cleaned by boiling in 30% concentration hydrogen peroxide following the procedure described in Taylor et al. (2007) and Al-Handal & Wulff (2008). Cleaned diatom suspension was placed on a coverslip and left to dry at room temperature then mounted in Naphrax® (Brunel microscope Ltd.,

Chippenham, UK). Diatoms were examined and photographed by using Zeiss Axiophot 2 imaging microscope (Carl Zeiss AB), at the Department of Marine Biology, Marine Science Centre, University of Basrah. GBIF (2021) was followed for checking the scientific names and authorities (excluding the year of authority) of all concerned diatom species.

Relative Abundance (RA)

Relative abundance of all species encountered in both natural and cultivated samples was estimated by counting 400 valves in each slide. Counting was made in transapical lines across the cover slip until 400 counts were reached. RA was estimated according to the following formula:

$$RA = (n/N) \times 100$$

Where n= number of valves of each species counted and N= total number of valves of all species (400).

Results

Environmental Parameters

The environmental features of the three sites are shown in Table 1. Air temperature reached its highest value (42°C) in July and its lowest value (38°C) in August. The highest water temperature of 33 °C was recorded at site 2, while the lowest temperature reading of 31 °C was recorded at site 1. Narrow fluctuation of pH was observed during the sampling, the maximum value of 8 was at site 3 and the minimum value of 7.2 was at site 1. The lowest value of salinity (1.5 psu) was recorded at site 1, while the highest value (5.2 psu) was recorded at site 3.

Table 1: Environmental parameters at the study sites in Shatt Al-Arab River during July and August 2020.

| Parameters | Sites | | |
|------------------------|--------|--------|--------|
| | Site 1 | Site 2 | Site 3 |
| Air temperature (°C) | 38 | 42 | 38 |
| Water temperature (°C) | 31 | 33 | 32 |
| pH | 7.2 | 7.8 | 8 |
| Salinity (psu) | 1.5 | 3.2 | 5.2 |

Diatom Species Composition

In total, 67 diatom species were identified at all sites. These taxa are listed alphabetically in Table 2. Epipellic diatom species assemblages included freshwater forms (25%), brackish water forms (25%) and marine species (26%), the remainder (24%) were of variable undefined ecological preferences from marine to fresh. In general, most of the encountered species (93%) were pennate, constituting 64 species belonging to 28 genera. Centric diatoms constituted merely 7% of the diatom community and included five species belonging to three genera. *Nitzschia* was the most common genus with 15 species distributed at all sites, followed by *Tryblionella* with six species, *Navicula* with four species, *Cyclotella* with three

species and *Gyrosigma* with three species. Other genera were less diverse and were represented by a single species (Table 2). Higher number of species was in August at site 3, while lower number was in July at site 2. five species (*Craspedostauros britannicus*, *Nitzschia invisitata*, *Pinnularia quadratarea*, *Simonsenia* sp. and *Tryblionella plana*) found in this study were not previously reported from Iraq and considered as new to the region. Among them, *Synedropsis abufloensis* is new to science and its type material has been deposited in the Botanscher Garten und Botanischer Museum, Berlin, under reference no. B 40 0045147. Description and distinguishing features of this species will be dealt with in detail in a separate article.

Table 2: Ecology and relative abundance (RA%) of the natural diatoms assemblage at the study sites. f: freshwater, b: brackish water, m: marine, un: unknown. Numbers under each site represent RA%.

| Species | Figure | Site 1 | Site 2 | Site 3 | Habitat |
|--|----------------|--------|--------|--------|---------|
| <i>Achnanthes brevipes</i> var. <i>intermedia</i> (Kützing) Cleve | Pl. 2: 4 & 5 | 1 | - | - | m, b |
| <i>Amphora copulata</i> (Kützing) Schoeman & Archibald | Pl. 5: 10 | 3 | 1 | - | f |
| <i>Bacillaria paxillifera</i> (O.F.Müller) Hendey | Pl. 5: 4 | 2.75 | - | - | b, m |
| <i>Berkeleya scopulorum</i> (Brébisson ex Kützing) Cox | Pl. 2: 14 | - | - | 0.75 | m |
| <i>Brachysira</i> sp. | Pl. 3: 7 | - | - | 0.25 | un |
| <i>Caloneis permagna</i> (Bailey) Cleve | Pl. 2: 8 | 1 | - | - | b |
| <i>Campylodiscus bicostatus</i> Grunow | Pl. 6: 12 | - | - | 0.25 | b |
| <i>Cocconeis euglypta</i> Ehrenberg | Pl. 2: 9 | 1 | 0.75 | - | f, b |
| <i>Cocconeis pediculus</i> Ehrenberg | Pl. 2: 11 | 3.5 | - | - | f, b |
| <i>Craspedostauros britannicus</i> Cox | Pl. 5: 6 | - | - | 2 | m |
| <i>Ctenophora pulchella</i> (Ralfs ex Kützing) Williams & Round | Pl. 1: 11 | - | - | 0.25 | b |
| <i>Cyclotella meneghiniana</i> Kützing | Pl. 1: 2 & 3 | 3 | 2.5 | 5.25 | m, f |
| <i>Cyclotella striata</i> (Kützing) Grunow | Pl. 1: 1 | 2.25 | 6.25 | 10 | f, b |
| <i>Cyclotella</i> sp. | Pl. 1: 4 | - | 2.75 | 5.5 | un |
| <i>Diatoma vulgare</i> Bory | Pl. 1: 7 & 8 | 1.5 | - | 0.25 | f, b |
| <i>Entomoneis corrugata</i> (Giffen) Witkowski, Lange-Bertalot & Metzeltin | Pl. 6: 10 & 11 | 7.5 | 6.25 | 3.75 | b |
| <i>Fallacia pygmaea</i> (Kützing) Stickle & D.G.Mann | Pl. 5: 9 | - | - | 0.75 | b, f |
| <i>Fragilaria koensabbei</i> Al-Handal & Al-Shaheen | Pl. 1: 13 | - | 0.25 | 0.25 | f |
| <i>Giffenia cocconeiformis</i> (Grunow) Round & Basson | Pl. 5: 7 | - | - | 0.5 | m, b |
| <i>Gomphonella olivacea</i> Rabenhorst | Pl. 2: 6 | 2.25 | - | - | m |
| <i>Gomphonema affine</i> Kützing | Pl. 2: 3 | 0.75 | - | - | f |
| <i>Gyrosigma acuminatum</i> (Kützing) Rabenhorst | Pl. 3: 11 | 0.5 | - | - | f, b |
| <i>Gyrosigma wormleyi</i> (Sullivant) Boyer | Pl. 3: 8 | 0.75 | - | - | f |
| <i>Gyrosigma</i> sp. | Pl. 3: 9 | 1.5 | - | 0.5 | un |

| | | | | | |
|---|---------------|------|------|------|---------|
| <i>Halamphora</i> sp. 1 | Pl. 5: 11 | 4 | - | 4.5 | un |
| <i>Halamphora</i> sp. 2 | Pl. 5: 12 | - | - | 3.75 | un |
| <i>Lindavia</i> sp. | Pl. 5: 6 | 2.75 | 2.5 | - | un |
| <i>Mastogloia smithii</i> Thwaites ex W. Smith | Pl. 2: 2 | - | 0.5 | - | b |
| <i>Navicula erifuga</i> Lange-Bertalot | Pl. 3: 1 & 2 | 6.5 | 3 | 0.75 | b |
| <i>Navicula viridula</i> var. <i>Rostellata</i> (Kützing) Cleve | Pl. 3: 3 | 4.75 | - | - | f |
| <i>Navicula</i> sp. 1 | Pl. 3: 4 | 0.75 | - | - | un |
| <i>Navicula</i> sp. 2 | Pl. 3: 5 | - | 4.75 | - | un |
| <i>Nitzschia brevissima</i> Grunow | Pl. 4: 14 | 4.75 | 6.75 | - | b |
| <i>Nitzschia clausii</i> Hantzsch | Pl. 5: 3 | 6.5 | 8.75 | 7.25 | b, f |
| <i>Nitzschia elegantula</i> Grunow | Pl. 4: 10 | 2.75 | 5 | 0.25 | f |
| <i>Nitzschia filiformis</i> (W.Smith) Hustedt | Pl. 4: 13 | 3.5 | 3 | - | b |
| <i>Nitzschia gracilis</i> Hantzsch | Pl. 4: 11 | 0.75 | 5.25 | 1.25 | f |
| <i>Nitzschia hybrida</i> Grunow | Pl. 4: 2 | - | - | 1.75 | b |
| <i>Nitzschia invisitata</i> Hustedt | Pl. 5: 8 | 3.25 | - | - | f |
| <i>Nitzschia lorenziana</i> Grunow | Pl. 4: 7 | - | - | 4 | b |
| <i>Nitzschia obtusa</i> W.Smith | Pl. 5: 1 & 2 | 5.25 | 6.75 | - | m, b |
| <i>Nitzschia palea</i> (Kützing) W.Smith | Pl. 4: 8 & 9 | 6 | 8.25 | 9.5 | f |
| <i>Nitzschia scalpelliformis</i> Grunow | Pl. 4: 6 | - | 6.25 | 2.75 | b |
| <i>Nitzschia sigma</i> W.Smith | Pl. 4: 1 | 3.5 | - | 5 | m, b, f |
| <i>Nitzschua umbonata</i> (Ehrenberg) Lange-Bertalot | Pl. 4: 12 | 3.75 | - | 3.75 | m, f |
| <i>Nitzschia</i> sp. 1 | Pl. 4: 4 | - | - | 0.75 | un |
| <i>Nitzschia</i> sp. 2 | Pl. 4: 5 | - | - | 0.75 | un |
| <i>Petrodictyon gemma</i> (Ehrenberg) D.G.Mann | Pl. 6: 9 | - | - | 7.5 | m |
| <i>Pinnularia quadratarea</i> (A. Schmidt) Cleve | Pl. 5: 5 | - | - | 0.75 | m |
| <i>Placoneis clementis</i> (Grunow) Cox | Pl. 2: 12 | - | - | 2 | f |
| <i>Planothidium delicatulum</i> (Kützing) Round & Bukhtiyarova | Pl. 2: 7 | 0.5 | - | - | f, b |
| <i>Pleurosigma angulatum</i> (Queckett) W.Smith | Pl. 3: 10 | - | - | 0.25 | m |
| <i>Prestauroneis crucicula</i> (W.Smith) Genkal & Yarushina | Pl. 2: 10, 13 | 1.75 | 1 | - | m, f |
| <i>Rhoicosphenia abbreviata</i> (C.Agardh) Lange-Bertalot | Pl. 2: 1 | - | 0.5 | - | f |
| <i>Scoliopleura basrensis</i> Al-Handal & Pennesi | Pl. 3: 6 | 0.25 | - | - | b |
| <i>Simonsenia</i> sp. | Pl. 1: 9 | - | - | 2.75 | un |
| <i>Surirella striatula</i> Turpin | Pl. 6: 8 | - | - | 0.5 | un |
| <i>Surirella</i> sp. 1 | Pl. 6: 7 | - | - | 0.25 | un |
| <i>Synedropsis abufloensis</i> Al-Handal, Al-Shaheen & Al-Saedy | Pl. 1: 12 | - | 4 | - | un |
| <i>Thalassiosira</i> sp. | Pl. 1: 5 | - | - | 0.5 | un |
| <i>Tryblionella coarctata</i> (Grunow) D.G.Mann | Pl. 6: 4 | 4 | - | - | m |
| <i>Tryblionella granulata</i> (Grunow) D.G.Mann | Pl. 6: 6 | - | 3.75 | 1.75 | m |

| | | | | | |
|---|-----------|------|------|------|----|
| <i>Tryblionella hungarica</i> (Grunow) Frenguelli | Pl. 6: 3 | 2.25 | - | 0.25 | b |
| <i>Tryblionella littoralis</i> (Grunow) D.G.Mann | Pl. 6: 1 | - | 5.75 | - | m |
| <i>Tryblionella plana</i> (W.Smith) Pelletan | Pl. 6: 2 | - | 4.25 | - | m |
| <i>Tryblionella</i> sp. 1 | Pl. 6: 5 | - | - | 4.25 | un |
| <i>Williamsella iraqiensis</i> Al-Handal & Kociolek | Pl. 1: 10 | - | 0.25 | 0.25 | b |

Effect of Temperature on Diatom Species Recovery

The recovery rate of diatom species at all sites appeared to be rather similar. A total of 40, 38 and 37% of all taxa encountered at all three sites respectively were able to recover from desiccation. Recovering ability of those species varies with variable temperature. Suitable temperature for most species ranged between 15 and 25 °C, although few species flourished at higher temperatures. No growth was observed at 40 °C. Figures 2, 3 and 4 illustrate the time and abundance (RA%) of taxa recovered at all sites. To better describe the ability of species to recover, each species is treated separately in the following and taxa are arranged depending on their recovery time and abundance after submerging dry material in water.

Nitzschia palea (Pl. 4, Figs. 8 & 9): This is the only species that recovered at all sites. Its regrowth started after three days and constituted the highest growth rate with a relative abundance of 78% at site 3 where it dominated diatom assemblage. The species was able to recover at all temperature treatments with high growth frequency.

Nitzschia filiformis (Pl. 4, Figs. 3 & 13): This species was found only at sites 1 and 2. It recovered after three days with a high growth rate, constituting 62.2% of the total recovered diatom species at site 1 for 10 °C and 39.9% for 30 °C at site 1.

Tryblionella sp. 1 (Pl. 6, Fig. 5): This species was observed only at site 3. Its regrowth began after three days with a growth rate constituting 49.28% of the recovered diatom species at this site for 10 °C.

Synedropsis abuflosensis (Pl. 1, Fig. 12): This is a new species, recorded only at site 2. It took three days to recover with high growth rate, constituting 41% of the total recovered diatom taxa at 10 °C, and 35.5% at 25 °C.

Nitzschia umbonata (Pl. 4, Fig. 12): This species appeared at sites 1 and 3. It returned after three days only at site 1 with a high growth rate accounting for 35.4% of the recovered diatom species at 25 °C and 25.9% at 30 °C.

Fragilaria koensabbei (Pl. 1, Fig. 13): This species was observed at sites 2 and 3. It was able to grow after three days of incubation. The best growth rate at site 2 with a relative abundance of 26.3% at 10 °C and 24% at 30 °C.

Nitzschia gracilis (Pl. 4, Fig. 11): This species was found at all sites. Its regrowth began after three days only at sites 1 and 2. It reached its largest growth rate at site 1, accounting for 26% and 20.3% of the recovered diatoms at 15 and 20 °C, respectively.

Entomoneis corrugata (Pl. 6, Figs.10 & 11): This species started to appear after three days at all sites with an ability to regrow at wider temperature range (15-30

°C), with the maximum relative abundance of 25.8% at 20 °C in site 3 and 15.8% at 20 °C in site 2.

Cyclotella striata (Pl. 1, Fig. 1): This species appeared at all sites. Its regrowth started after three days at sites 2 and 3. The highest growth rate was observed at site 3 with a relative abundance of 25.1% at 10 °C. *C. striata* exhibited ability to regrow and survive at 35 °C with a growth rate of 22%. *C. striata* and *N. palea* were the only species that could grow at 35 °C.

Nitzschia sp. 1 (Pl. 4, Fig. 4): This species was found at site 3. It began to regrow after six days, with a growth rate of 19.8% of the total recovered diatom species at 30 °C.

Williamsella iraqiensis (Pl. 1, Fig. 10): This species was observed at sites 2 and 3. It began to regrow after three days at both sites, with the highest growth rates of 17.5% and at 9.5% at 20 and 15 °C, respectively at site 2.

Cyclotella menighiniana (Pl. 1, Figs. 2 & 3): This species was found at all sites. It took three days to regrow at sites 2 and 3, with the highest growth rate of 10.63% at 10 °C at site 3.

Nitzschia elegantula (Pl. 4, Fig. 10): This species was found only at site 3. It recovered after three days, with the highest growth rate of 10.8% at 25 °C.

Thalassiosira sp. (Pl. 1, Fig. 5): This species appeared at site 3. It was recovered after three days, with the best growth rate of 9.8% at 25 °C.

Navicula erifuga (Pl. 3, Figs. 1 & 2): It was observed at site 1. Its recovery started after three days with a relative abundance of 9.5% at 15 °C.

Cyclotella sp. (Pl. 1, Fig. 4): This species was observed only at site 3. It recovered after three days and had the highest growth rate of 6.8% at 20 °C.

Surirella sp. 1 (Pl. 6, Fig. 7): This species appeared at site 3 only. Its regrowth started after three days, with a relative abundance of 6.8% at 30 °C.

Amphora copulata (Pl. 5, Fig. 10): This species was found at site 2 only. It started to regrow after three days, with growth rate composing 6.25% of the total recovered diatom species at this site for 20 °C.

Caloneis permagna (Pl. 2, Fig. 8): This species was found at site 1 only. After three days of incubation, its growth rate accounted for 4.2% of the overall recovered diatom species at 25 °C.

The rest of the recovered taxa which included *Cocconeis euglypta*, *Lindavia* sp., *Navicula viridula* var. *rostellata*, *Nitzschia brevissima*, *Nitzschia clausii*, *Tryblionella coarctata*, *Tryblionella plana*, *Halamphora* sp. 2, *Petrodictyon gemma*, *Surirella* sp. 2, *Nitzschia lorenziana*, *Gyrpsigma* sp. did not exhibit any significant growth rate and their relative abundance was almost less than 1% of the total recovered assemblage (Table 2).

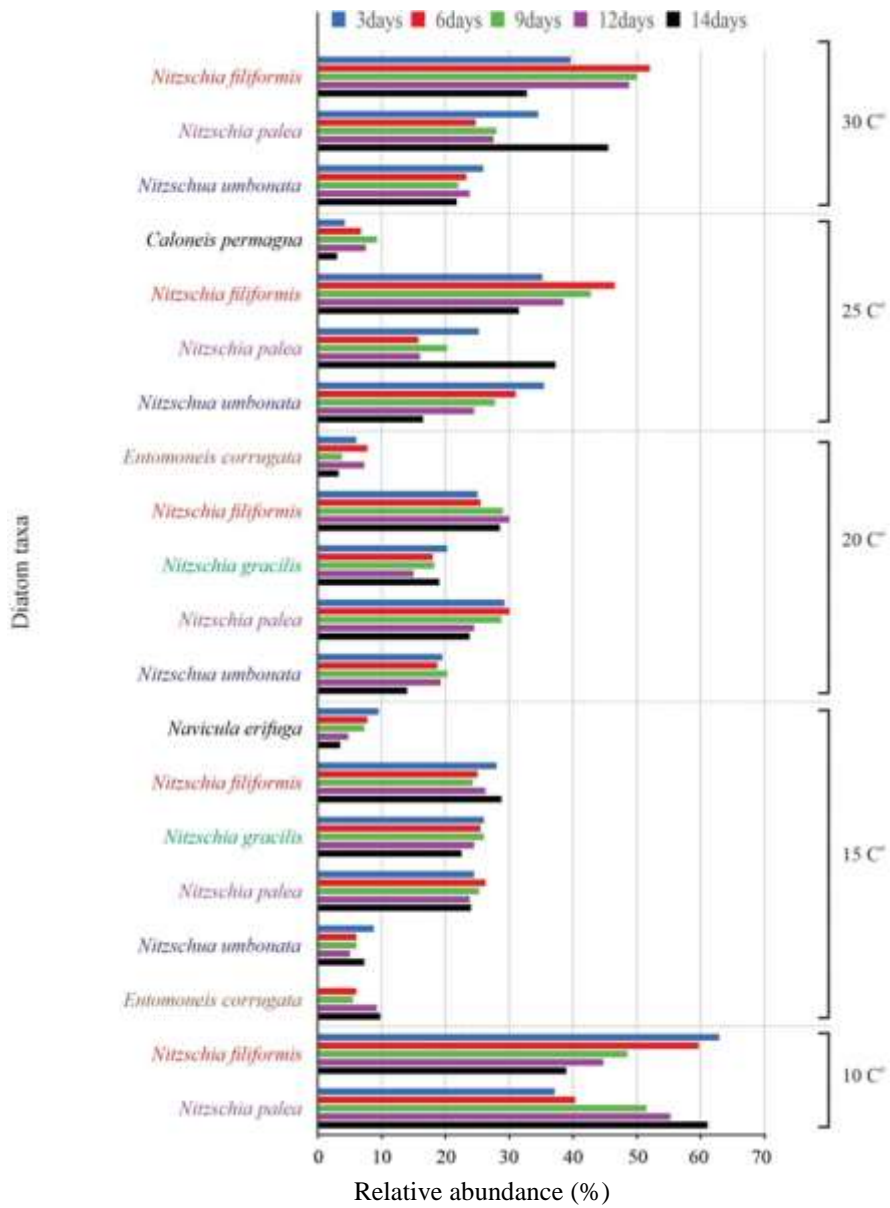


Figure 2: Relative abundance and recovery time of diatom species with different temperatures at site 1.

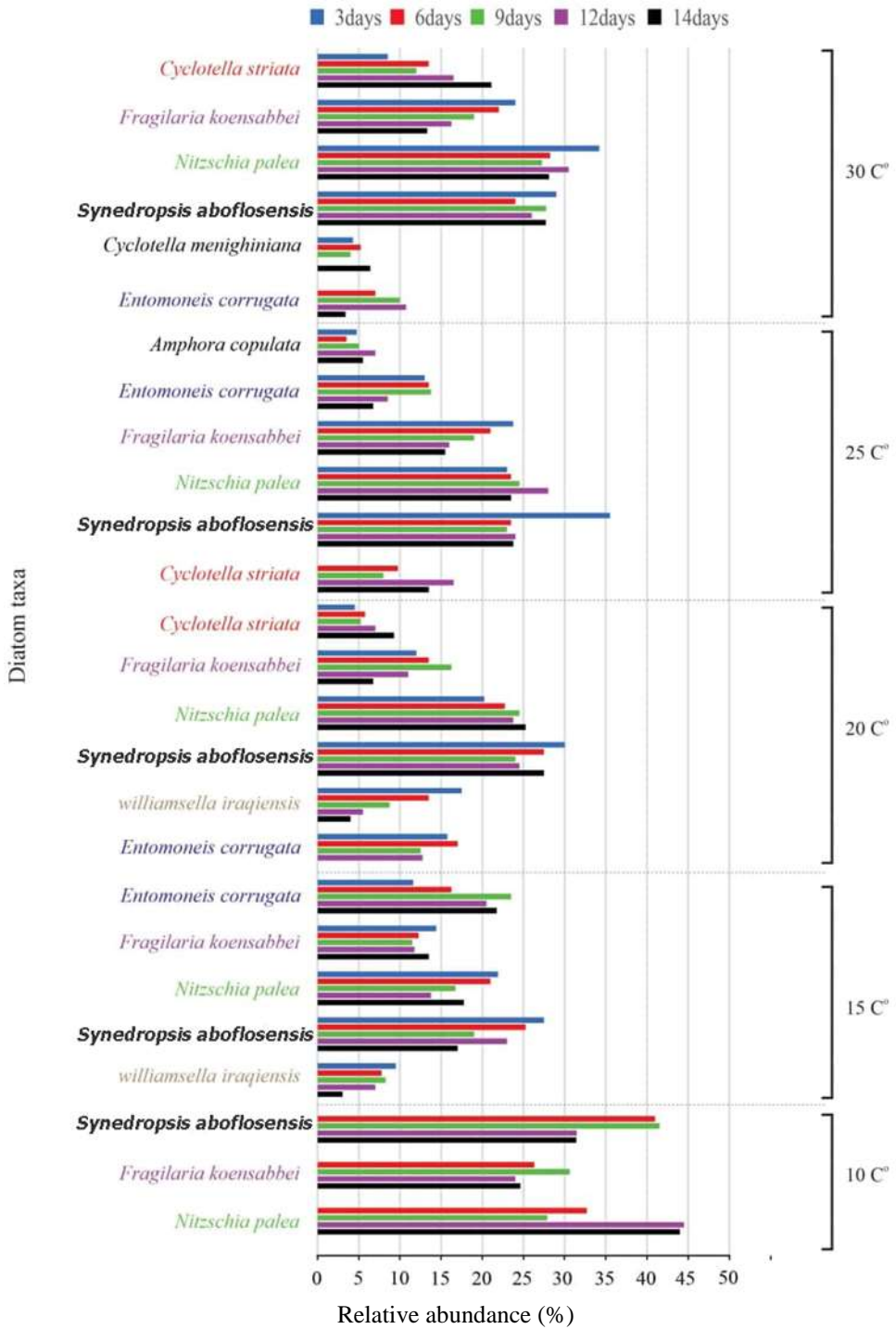


Figure 3: Relative abundance and recovery time of diatom species with different temperatures at site 2.

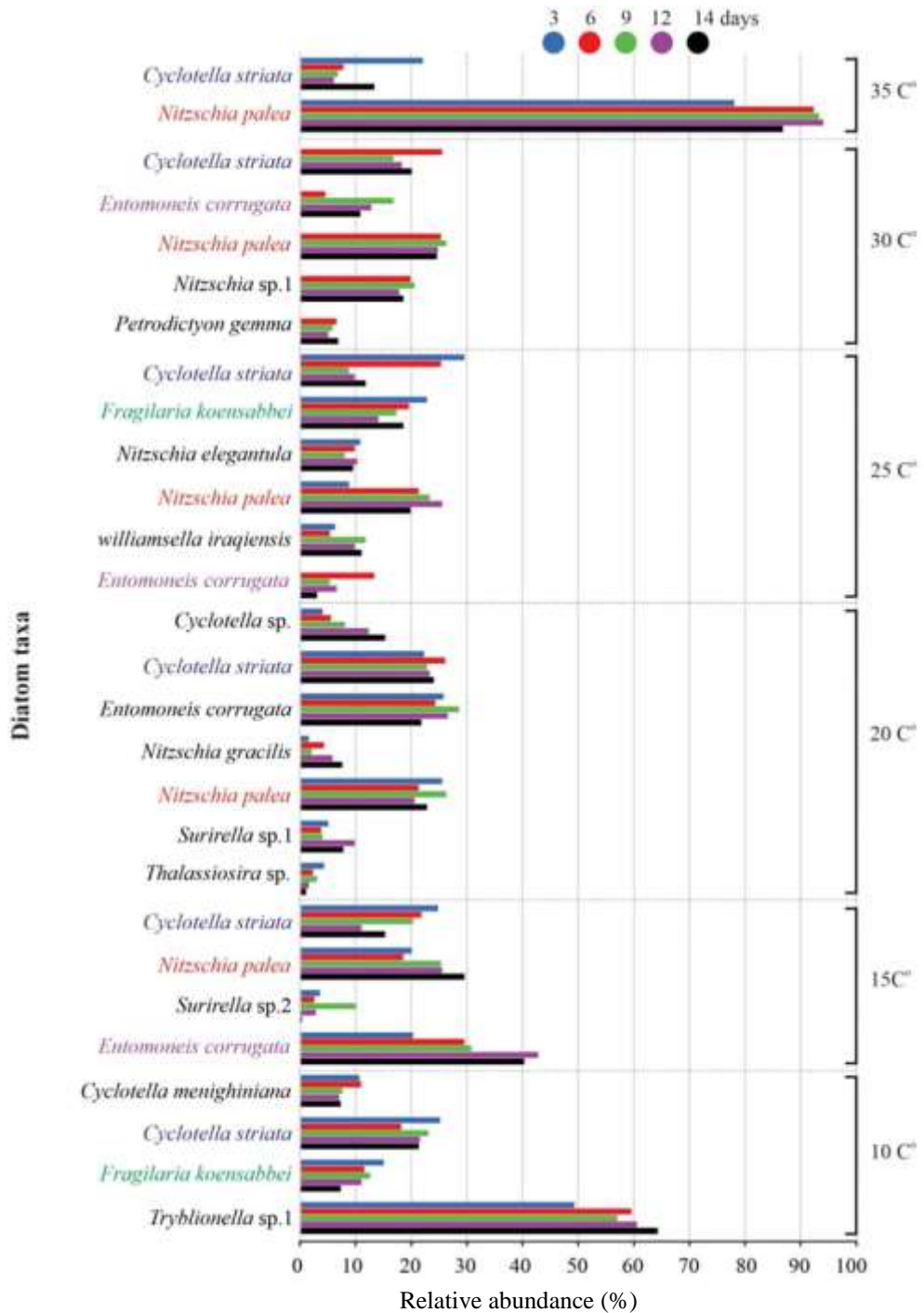


Figure 4: Relative abundance and recovery time of diatom species with different temperatures at site 3.

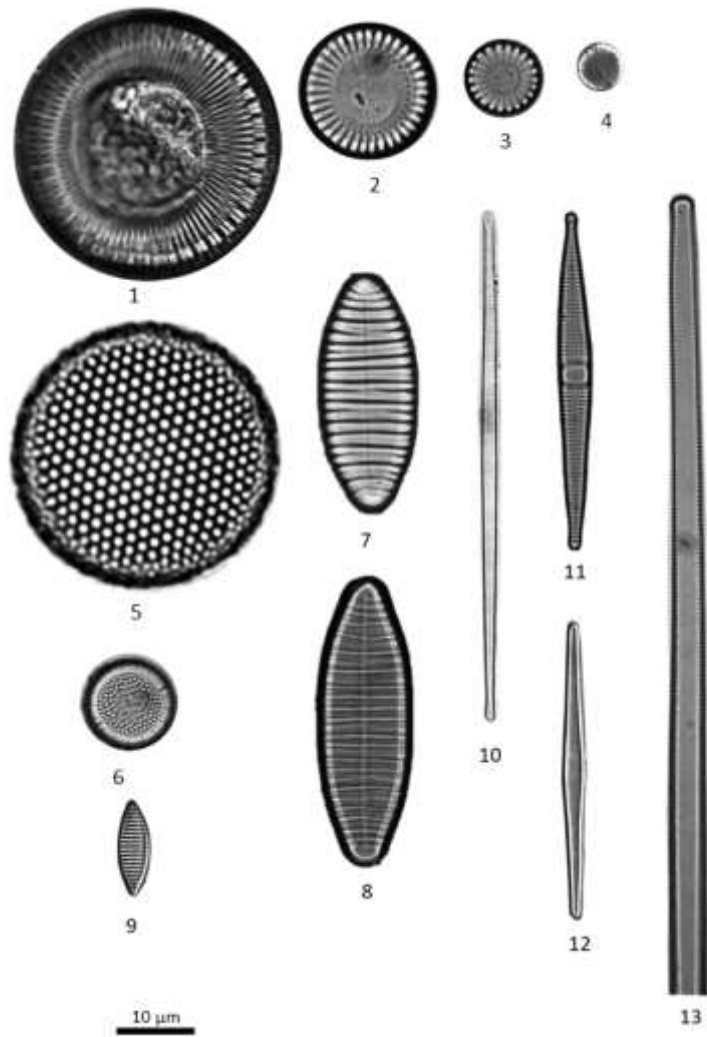


Plate 1: L. M. images of some benthic diatoms from Shatt Al-Arab river, Basrah, Iraq.

1. *Cyclotella striata*, 2, 3. *Cyclotella menighiniana*, 4. *Cyclotella* sp., 5. *Thalassiosira* sp., 6. *Lindavia* sp., 7, 8. *Diatoma vulgaris*, 9. *Simonsenia* sp., 10. *Williamsella iraqiensis*, 11. *Ctenophora pulchella*, 12. *Synedropsis abuflosensis*, 13. *Fragilaria koensabbei*.

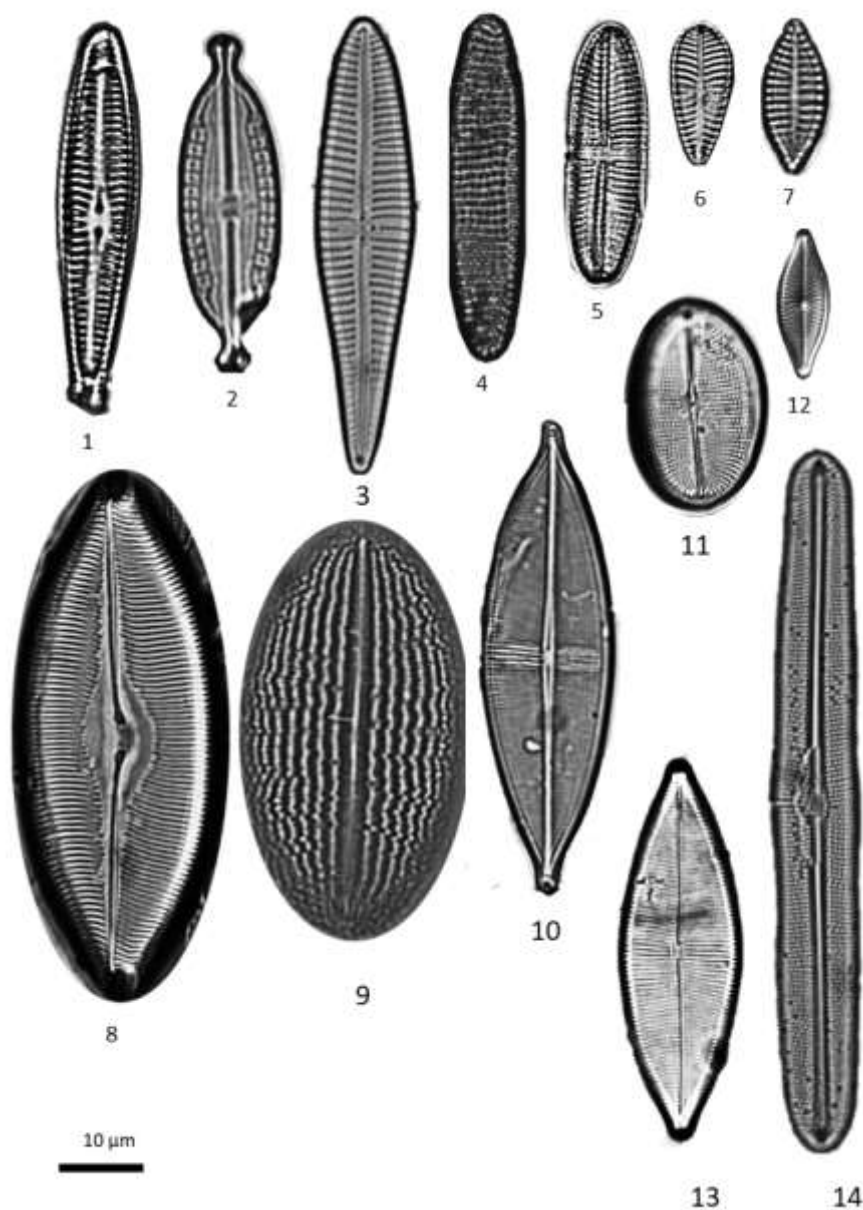


Plate 2: L. M. images of some benthic diatoms from Shatt Al-Arab river, Basrah, Iraq.

1. *Rhoicosphenia abbreviata*, 2. *Mastogloia* aff. *Smithii*, 3. *Gomphonema affine*, 4. *Achnanthes brevipes* var. *intermedia* (sternum valve), 5. *Achnanthes brevipes* var. *intermedia* (raphe valve), 6. *Gomphonella olivacea*, 7. *Planothidium delicatulum*, 8. *Caloneis permagna*, 9. *Cocconeis euglypta*, 10, 13. *Prestauroneis crucicula*, 11. *Cocconeis pediculus*, 12. *Placoneis clementis*, 14. *Berkeleya scopulorum*.

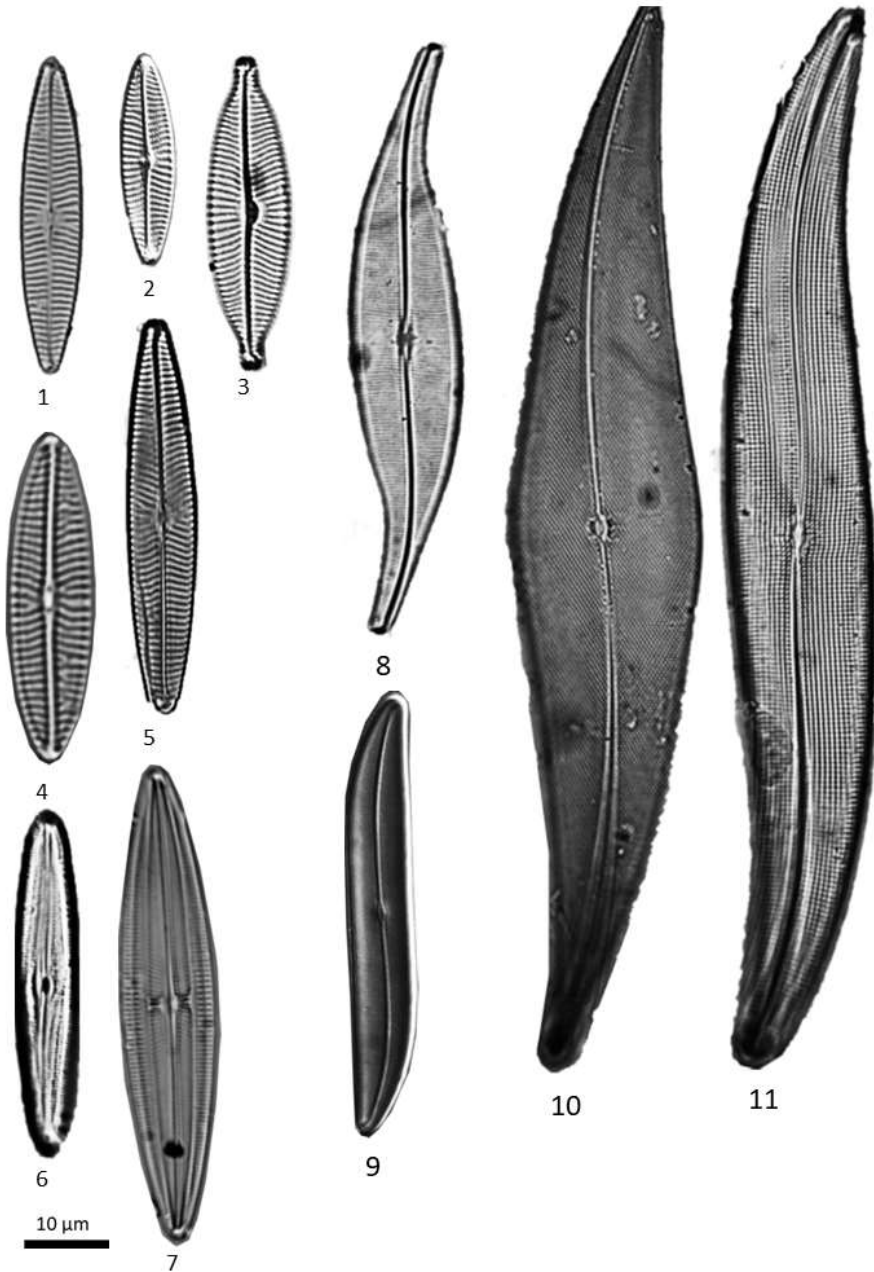


Plate 3: L. M. images of some benthic diatoms from Shatt Al-Arab river, Basrah, Iraq.
 1, 2. *Navicula erifuga*, 3. *Navicula viridula* var. *rostellata*, 4. *Navicula* sp. 1, 5. *Navicula* sp. 2, 6. *Scoliopleura basrensis*, 7. *Brachysira* sp., 8. *Gyrosigma wormleyi*, 9. *Gyrosigma* sp., 10. *Pleurosigma angulatum*, 11. *Gyrosigma acuminatum*.

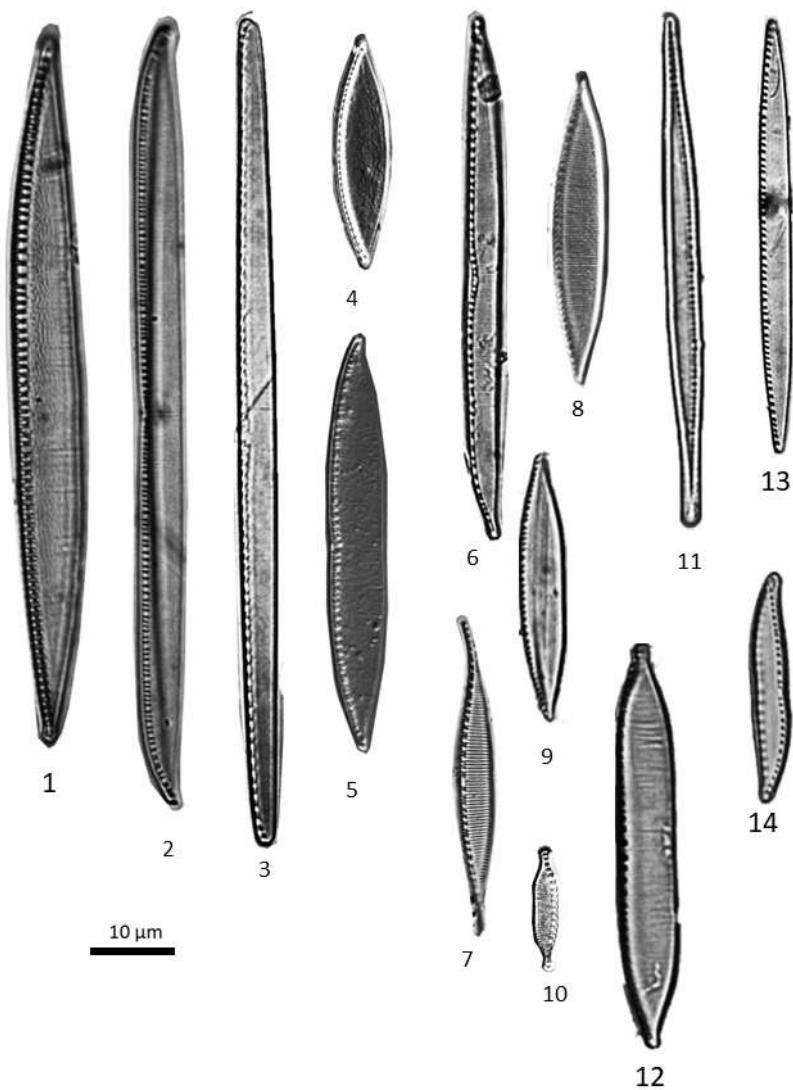


Plate 4: L. M. images of some benthic diatoms from Shatt Al-Arab river, Basrah, Iraq.

1. *Nitzschia sigma*, 2. *Nitzschia hybrida*, 3, 13. *Nitzschia filiformis*, 4. *Nitzschia* sp. 1, 5. *Nitzschia* sp. 2, 6. *Nitzschia scalpelliformis*, 7. *Nitzschia lorenziana*, 8, 9. *Nitzschia palea*, 10. *Nitzschia elegantula*, 11. *Nitzschia gracilis*, 12. *Nitzschua umbonate*, 14. *Nitzschia brevissima*.

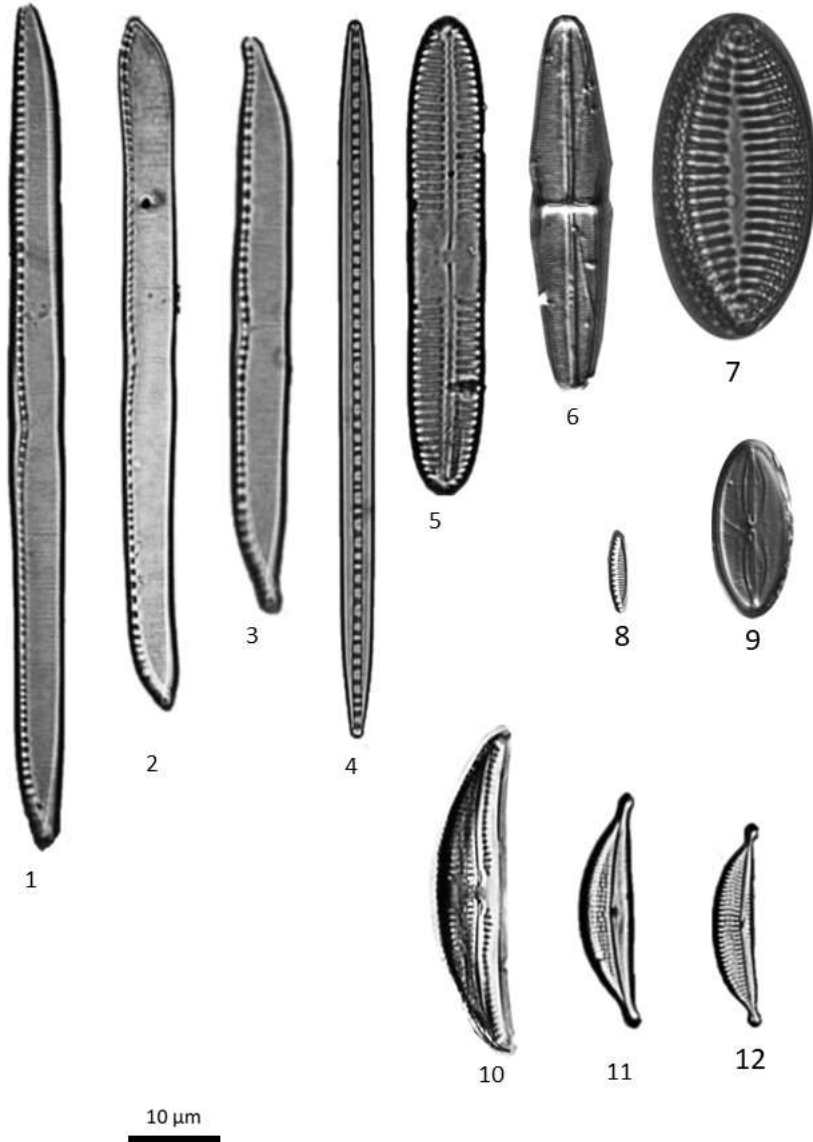


Plate 5: L. M. images of some benthic diatoms from Shatt Al-Arab river, Basrah, Iraq.

1, 2. *Nitzschia obtusa*, 3. *Nitzschia clausii*, 4. *Bacillaria paxillifera*, 5. *Pinnularia quadratarea*, 6. *Craspedostauros britannicus*, 7. *Giffenia cocconeiformis*, 8. *Nitzschia invisitata*, 9. *Fallacia pygmaea*, 10. *Amphora copulata*, 11. *Halamphora* sp. 1, 12. *Halamphora* sp. 2.

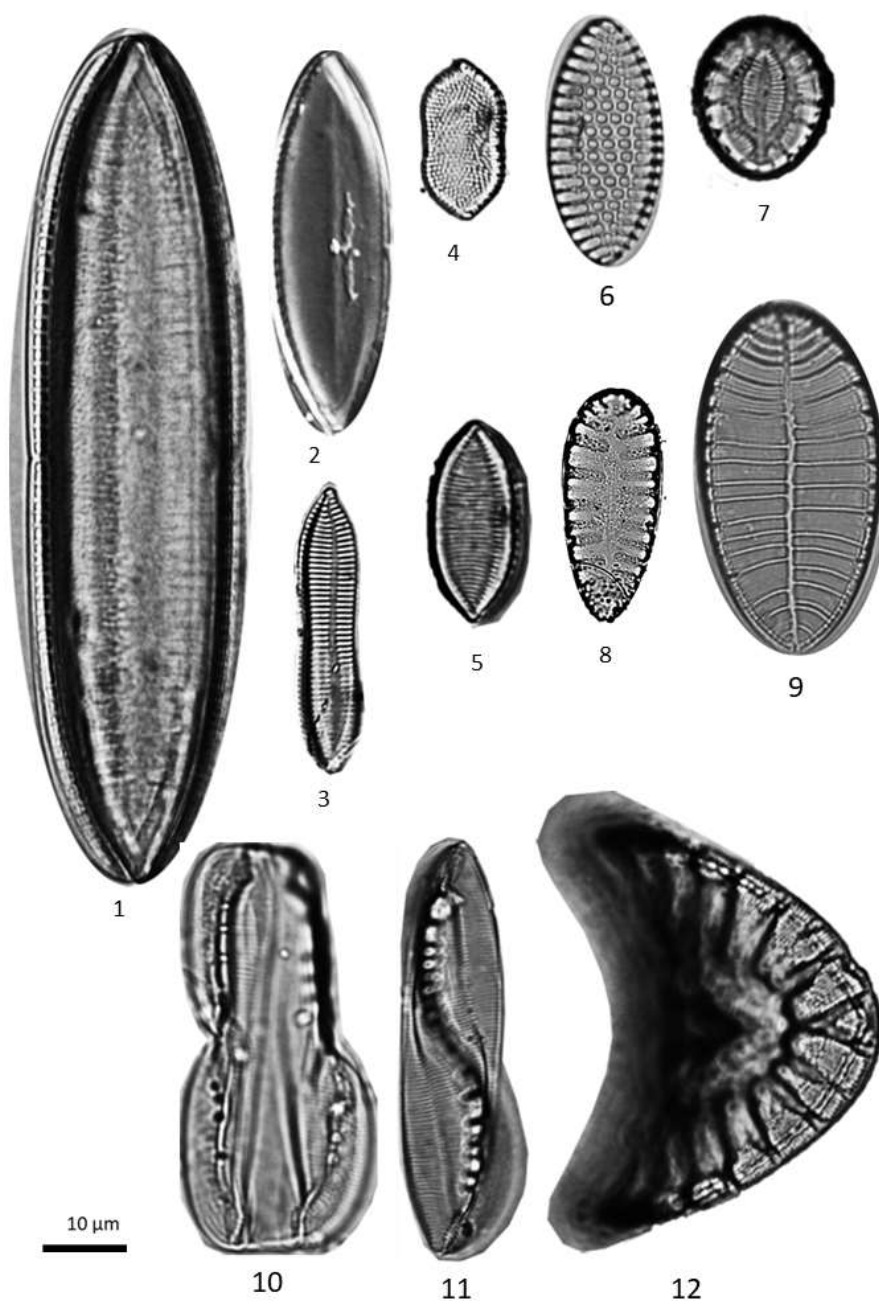


Plate 6: L. M. images of some benthic diatoms from Shatt Al-Arab river, Basrah, Iraq.

1. *Tryblionella littoralis*, 2. *Tryblionella plana*, 3. *Tryblionella hungarica*, 4. *Tryblionella coarctata*, 5. *Tryblionella* sp. 1, 6. *Tryblionella granulata*, 7. *Surirella* sp. 1, 8. *Surirella striatula*, 9. *Petrodictyon gemma*, 10, 11. *Entomoneis corrugata*, 12. *Campylodiscus* sp.

Discussion

Despite of the limited sampling, both in time and number of samples, yet several of the encountered taxa were not previously reported in Shatt Al-Arab River and constitute new records to the diatom flora of Iraq (Al-Handal & Abdulla, 1994; Al-Handal & Al-Shaheen, 2019). This could be attributed to the ongoing changes in the environmental conditions in the river which lead to either disappearance or appearance of new organisms (Al-Mayah & Al-Asadi, 2018).

In the present investigation, an attempt to understand how diatoms respond to environmental stress, especially to high temperatures, was made. Therefore, epipellic diatoms collected from coastal line of Shatt Al-Arab river, were exposed to desiccation at 50 °C in order to monitor their ability to recover such harsh conditions. Diatoms tolerance to desiccation is not well known although few studies pointed to limited number of species with certain level of regrowth after exposing to prolonged period of exposure to air (Hargraves & French, 1975; Schmid, 2009; Souffreau et al., 2010).

One of the most common recovered species was *Nitzschia palea* which appeared at all sites and constituted 78% of the total recovered diatoms at site 3. It is not unlikely that this species reappeared in such high frequency, it is well known to occur in different environmental conditions (Ahirwar et al., 2020) and is common in lotic and lentic habitats and sometimes the most abundant taxon (Trobajo et al., 2009). It is also tolerant to high levels of toxic metal pollutants and pesticides (Wang et al., 2020). This capability of surviving in extreme conditions, such as desiccation, is attributed to its capability of tolerating wide environmental fluctuations. *N. palea* had a maximum growth rate at all temperatures (10-35 °C). Previously, it was thought that this species is unable to grow at temperatures above 30 °C (Beliveau & Hickman, 1982), whereas in this study it grew at 35 °C, providing evidence that it can tolerate a higher temperature range.

Nitzschia filiformis is another species that recovered with a high growth rate, and accounted for 62.2% of the total diatom species recovered at site 1. *N. filiformis* has a wide ecological preference and was found to flourish in areas polluted by industrial effluents (Lange-Bertalot et al., 2017). This species is one of the most abundant tube-forming diatoms (Carr & Hergenrader, 1987; Fricke et al., 2017). This might explain its ability to withstand desiccation. The present results indicated that its optimum growth was at 10 °C and 30 °C, with less appearance at the other treatments.

Tryblionella sp. 1 was one of the most recovered diatoms and constituted 49.28% at 10 °C at site 3. It was only recovered at this temperature, indicating its narrow temperature preference. Since the definite identity of this species is not known, it was not possible to relate its desiccation tolerance to any ecological preference.

The newly found species, *Synedropsis abuflosensis* occurred at site 2 only. It was recovered with a high growth rate of 41% at 10 °C and 35.5% at 25 °C. *Synedropsis* is a small genus with only few representatives. It was not previously recorded from all Asian inland or marine habitats. Ecology of this new taxon is

different from all other known *Synedropsis* species by occurring as benthic and epiphytic on algal mats which add a new environmental preference to this genus whose taxa are either sea-ice forms (Hasle et al., 1994) or planktonic (Melo et al., 2003; Prasad & Livingston, 2005).

Nitzschua umbonata recovered at sites 1 with a growth rate of 35.4% at 25 °C and 25.9% at 30 °C. This species occurs sporadically in eu- to polytrophic, saprobically impacted freshwater habitats which are rather similar to Shatt Al-Arab River conditions. It is used as organic pollution indicator (Ndiritu et al., 2006; Simsek, 2018). Such environmental stress resistance may explain its regrowth after desiccation in the present study.

Fragilaria koensabbei is another species which recovered at sites 2 and 3 with a growth rate of 26.3% at 10 °C and 24% at 30 °C. The distribution and ecology of this species is not well known as it was recently described from Shatt Al-Arab river. It is common, however, in Southern Iraq as planktonic and epiphytic (Al-Handal & Al-Shaheen, 2019). The present results indicated that *F. koensabbei* regrowth was achieved at all temperature treatments except for 35 °C.

Nitzschia gracilis was recovered at sites 1 and 2 with largest growth rate of 26% and 20.3% at 15 and 20 °C, respectively. It was previously documented that favourable temperature of optimum growth of this species is in the range of 15-30 °C (Beliveau & Hickman, 1982) which coincides with the present finding. *N. gracilis* is a widely distributed species (Hartley et al., 1986; Krammer & Lange-Bertalot, 1988), but its environmental preference is rarely known. Its recovery in the present study, however, indicates its resistance to temperature extremes.

Entomoneis corrugata recovered at all sites with an ability to regrow at all temperature treatments except for 35 °C. It reached maximum relative abundance of 25.8% at 20 °C (site 3) and 15.8% at 20 °C (site 2). *E. corrugata* is common in Southern Iraq (Al-Handal & Al-Shaheen, 2019) but with limited distribution in the World (Witkowski et al., 2000). However, its common occurrence in Shatt Al-Arab River exhibits its tolerance to wide environmental fluctuations.

The two species of *Cyclotella*; *C. striata* and *C. menighiniana* showed noticeable recovery although their environmental preference vary considerably. *C. striata* is a marine to brackish water form and considered as good indicator to environmental changes (Abate et al., 2017). It was recovered at site 3 with a relatively high growth rate (25.1%) at 10 °C and showed the ability to grow at 35 °C, constituting 22% of all other taxa. *C. menighiniana* is an organic and industrial pollution tolerant and inhabit variable habitats (Buric et al., 2007). It was recovered at sites 2 and 3, with the highest growth rate of 10.63% at 10 °C at site 3.

A number of species including *Cyclotella* sp., *Surirella* sp. 1 and *Thalassiosira* sp. were able recover at site 3 only with relatively high relative abundance (Fig. 4). All these taxa are of marine origin which explains their occurrence at site 3 which is exposed to sea water during high tide. Their recovery indicates their ability to tolerate temperature extremes.

Other species which their recovery was confined to one site included *Navicula erifuga* and *Caloneis permagna* (site 1) and both *Amphora copulata* and

Williamsella iraqiensis (site 2). Their relative abundance was relatively small in comparison to the other taxa, but they exhibited noticeable tolerance to high temperature.

It was previously documented that some species of diatoms can survive desiccation by producing resting spores and resting cells, which is a successful way for surviving environmental stress (Hargraves & French, 1975; Souffreau, 2011). Resting cells act as a seed bank in the sediment (Jewson et al., 2006; Poulicková et al., 2008) which could explain the rapid spring blooms of diatoms. Resting cells and spores are also resistant to dark, cold and nutrient limited conditions (McQuoid & Hobson, 1995). According to Sanyal et al. (2019), resting spores of diatoms can survive for centuries in nature and the diatoms spores are still viable if the perfect conditions are given. The present results showed that the germination period for most of the species exposed to desiccation can occur within a short period, mostly after 72 hours after return of natural conditions, which coincide with Sanyal et al. (2019).

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