

**EFFECTS OF PHYSIO-CHEMICAL VARIATIONS ON
MODERN INTERTIDAL AND LAGOONAL BENTHIC
COMMUNITIES IN THE HYPERSALINE ENVIRONMENT
OF THE WESTERN ARABIAN GULF**

BY
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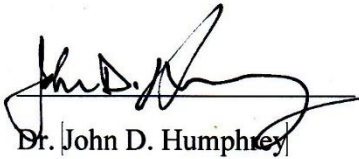
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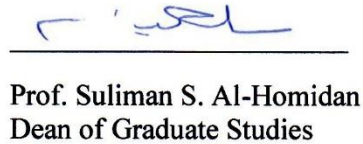
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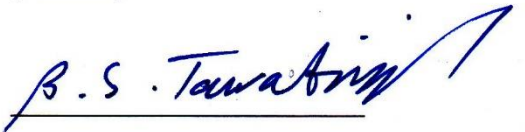

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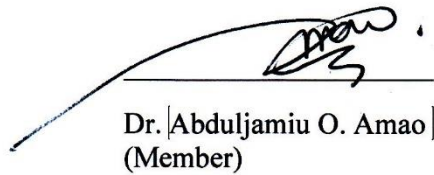

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Dedication

To Mike, Bassam, & Amao

For Everyone, For Greater Good |

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LIST OF ABBREVIATIONS

SEM	:	Scanning electron microscope
ICP-MS	:	Inductively coupled plasma mass spectrometry
LBF	:	Larger benthic foraminifera
SBF	:	Smaller benthic foraminifera
FOBIMO	:	FOraminiferal BIo-Monitoring
PSU	:	Practical Salinity Unit
PPM	:	Parts Per Million

ABSTRACT

Full Name : Sinatrya Diko Prayudi

Thesis Title : Effects of Physio-chemical Variations on Modern Intertidal and Lagoonal Benthic Communities in the Hypersaline Environment of the western Arabian Gulf

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The Arabian Gulf hosts diverse intertidal and coastal marine communities that persist despite extreme, fluctuating conditions. While prior studies focus on polluted areas, we examine the resilience of biocalcifying organisms in the western Gulf's relatively pristine zones to provide a natural baseline. We examined the resilience of intertidal biocalcifying organisms and benthic foraminiferal communities in the naturally stressed environment of the western Arabian Gulf. Specimens were collected from distinct locations in Saudi Arabia and Bahrain featuring extreme hypersaline conditions compared to the eastern Gulf. We focused on assessing the upper thermal limits and salinity tolerance of representative species, including gastropods (*Pirenella conica*, *Planaxis sulcatus*), ostracods (*Cyprideis* sp.), and diverse assemblages of benthic foraminifera. Controlled laboratory experiments simulated future ocean warming scenarios in the Gulf and replicated natural habitat settings. The foraminiferal materials were also examined for morphological abnormalities indicative of environmental stress. Our findings demonstrate both elevated thermal tolerance limits for gastropods and ostracods when immersed, as well as a high proportion (25%) of living foraminifera displaying various deformities despite minimal pollution levels. The occurrence of test abnormalities, particularly in mature specimens, likely results from salinity fluctuations and hypersaline constraints. As salinities frequently exceed 40 PSU in the western Gulf, we conclude these intertidal biocalcifying communities exhibit resilience to current extremes but face persisting environmental uncertainty amidst projections of intensifying future climate changes. Further experimental calibrations will elucidate lethal thresholds and the potential adaptations of these ecological indicators in an increasingly inhospitable region.

Keywords: physio-chemical parameters, benthic communities, hypersaline, Arabian Gulf

ملخص الرسالة

الاسم الكامل: سيناتريه ديكو برايو دي

عنوان الرسالة: تأثير التغيرات الفيزيائية والكيميائية على المجتمعات القاعية الحديثة في منطقة المد والجزر

التخصص: جيولوجيا

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تعد دراسة بيئة المد والجزر في الخليج العربي بما تحتويه من مجتمعات حيوية نشطة وكيفية تكيف هذه المجتمعات مع الظروف المتغيرة حولها باستمرار أحد الموضوعات العديدة التي تثير اهتمام العلماء بشكل هائل. حيث أن معظم هذه الدراسات تتعلق بالمناطق المتأثرة بشدة بالملوثات أو النشاطات البشرية، والمخاطر الناتجة المحتملة على التنوع البيولوجي. هناك القليل من الدراسات المناسبة التي أجريت توضح ردود فعل تلك المجتمعات داخل البيئة الطبيعية وكيفية تعاملها مع مثل هذه الظروف الفيزيائية والكيميائية دون أو مع تدخل بشري على نطاق صغير. في هذه الدراسة، نستكشف أماكن تواجد والحدود الإقليمية للمجتمعات القاعية التي تسكن منطقة المد والجزر الطبيعية في غرب الخليج العربي، إلى جانب معرفة رد فعل العينات الممثلة من هذه المجتمعات القاعية تجاه كل من التغيرات الفيزيائية والكيميائية في الماضي والحاضر، وربما المستقبل. من أجل تحقيق هدف الدراسة، تم استخدام عدة طرق مثل المسح الميداني والقياسات لتوصيف البيئة الطبيعية، وأخذ العينات الميدانية الممثلة الكافية للدراسة، والتجارب المعملية ومعالجة البيانات لإنتاج المعلومات النموذجية التي نحتاجها، والتحليل الإحصائي لتمثيل وقياس توقعاتنا للنتائج بطريقة سليمة. نظرًا لأن الجانب الفيزيائي الكيميائي يعتمد على التجارب المعملية التي تركز على تقييد درجة الحرارة، فإن بعض الكائنات الحية (بطنيات الأرجل، والصدفيات، والمتقبات) التي استخدمناها في التجارب الحرارية تُظهر قدرات حرارية عليا أعلى بشكل عام مقارنة بنفس الأصناف في مواقع مختلفة. من ناحية أخرى، بالنسبة للقيود الفيزيائية والكيميائية القائمة على القياس الميداني والمختبري، على الرغم من أن النتائج التي توصلنا إليها تعبر عن المواقع المختارة يمكن اعتبارها طبيعية أو غير مضطربة بناءً على مكونات المعادن الثقيلة وإجمالي الكربون العضوي، فإن المجتمعات القاعية (في هذه الحالة المتقبات) تظهر ميولاً مختلفة لتطوير التشوهات في شكل الصدفة الخاصة بها ولكنها تظل على قيد الحياة أثناء عمليات التغيير. من النتائج المتزامنة التي توصلنا إليها، حتى بدون التدخل البشري المباشر في هذه الأنظمة، فإن بعض المجتمعات القاعية داخل نظامنا تتغير بالفعل أو تتكيف للتعامل مع البيئة المتغيرة، سواء هذه الضغوطات فيزيائية أو كيميائية طبيعية.

الكلمات المفتاحية: المعايير الفيزيائية والكيميائية، المجتمعات القاعية، شديدة الملوحة، الخليج العربي

CHAPTER 1

INTRODUCTION

1.1 Climate Change Issues in the World Ocean and in the Arabian Gulf

Understanding the impact of environmental stressors, either derived from natural and/or anthropogenic sources is becoming a more urgent topic in the realm of science (Orr et al., 2020; Parmesan et al., 2013). As global issues like climate change and future uncertainties are still being widely discussed, assessing the interrelated complexity is interesting (Stewart, 2016; Vasconcelos and Orion, 2021; Finn et al., 2022). While some people prefer to believe that the impact of global climate change is not yet life-threatening for humankind within our timelines (Nisbet, 2009; Tol, 2008), it appears that several harmful effects are already taking a toll on sensitive faunal communities (Peñuelas et al., 2013; Folke et al., 2021).

When some scientist tried to address which communities are highly influenced by the upcoming (or current) climate change, they mostly targeted those that inhabit the realm in between land and ocean, in this case in the intertidal or coastal zones (Sany et al., 2014; Panda et al., 2020). Those biotic members within that realm, regardless of animals or plants, are quite insensitive towards the change of environment, either based on physical and/or chemical disturbance (Boyd et al., 2018; Luypaert et al., 2020). As the climate problem intensifies and later will be either in line with predictions of modelling

experiments and even exceeding expectations, the possible loss of biodiversity in the forthcoming climate change event could be quite significant within the intertidal communities and the adjacent marine realm (Boyd et al., 2018). Not to mention human interference towards nature, such as waste disposal and effluent discharge, land reclamation and dredging for urban development, and dangerous resource-intake processes are mostly occurring within the coastal area as a border between land and sea realm (Harley et al., 2006; He and Silliman, 2019).

To understand how severe the impact of those global issues that interfere with the ecological of intertidal biodiversity, a number of studies have already mentioned either in the specific region or widely in scale. For the impact of elevated temperature induced by global warming, an experimental study of thermal limits based on various biota across the realm is used, with the basic result that biota in the intertidal realm has a buffer between land-dwelling biota that have higher thermal limits and marine dweller have lower values (Sunday et al., 2012, 2011). Although some marine organisms may have a higher thermal limit as previously mentioned and not being threatened in the current timelines, while addressing the future change whether the land or sea surface temperature, their ability to survive will likely be surpassed by such impacts in the near future (Keppel et al., 2012; Ackerly et al., 2020). As for chemical disturbances, a number of publications have mentioned that chemical-induced stressors such as salinity, pH, and heavy metals within sediments can trigger abnormalities (i.e., morphological deformities and lethal affliction) that further induce more complexity to understand (Bucke, 1993; Geslin et al., 2000; Bukola and Zaid, 2015; Giam et al., 2018; Langston, 2018).

To make a long story short, studies related to the impact of physio-chemical stressors in the Arabian Gulf are somehow poorly explored, either locally or globally. Several studies have been done lately or are in progress, such as observing the severe effect of heavy metal contamination on the animals and plants within the Arabian Gulf (Youssef et al., 2016; El-Sorogy et al., 2019; Al-Kahtany et al., 2020), and the abnormal growth of animals due to stressors (Amao et al., 2016, 2018; Jawad and Ibrahim, 2021). However, these studies mainly focus on the actual contaminated or polluted areas where the occurrence of contaminants is undeniable. Not to mention that there is no specific study that addresses the impact of physical stressors that outlined the problem, especially the aspect of increasing temperature. Despite some research being done by observing the behavior and occurrence of marine animals within the various temperature in the Arabian Gulf's intertidal realms (Kaminski and Garrison, 2020; Kaminski et al., 2021a), no proper studies have been conducted to measure the actual thermal limits at which they die due to elevated temperature. In this study, we sampled, observed, and conducted experimental studies on the marine benthic animals) that inhabit the intertidal region in the Arabian Gulf, especially on the western side (around the eastern side of Saudi Arabia and in Bahrain).

1.2 The Arabian Gulf and its Physio-chemical Parameters

The Arabian Gulf or Persian Gulf or simply the Gulf, is a basic terminology for an open water with almost enclosed systems. The Gulf's basin is generated as a product of the Zagros Orogeny processes when two tectonic plates collided: the Arabian towards Asian, and later produces shallow tectonic depression in late Pliocene to Pleistocene (Sheppard et al., 2010). The semi-restricted systems that developed within the Gulf that are sometimes

referred to as a continuation of the Indian Ocean, are due to the low water circulation or exchange with the open ocean, almost similar to the Mediterranean Sea (Getahun, 1998; Nour, 2005). The entire water body covers around 22,600 km² (Purser, 1973; Amao et al., 2022) and the basin also elongated towards NW-SE axis, with 1000 km in length and narrowest part within the Strait of Hormuz (around 60 km) while the widest part reaching around 300 km (from the southwestern part of Qatar towards the Iranian side). The Gulf itself exhibits various bathymetry across the entire region and unique gradual change in value on both sides. The Kuwait-Saudi Arabia-Bahrain-Qatar-United Arab Emirates side has a more gently sloping bathymetry towards the central part, as compared with the steeper bathymetric gradient in the Iranian side (Purser, 1973; Amao et al., 2022; Figure 2).

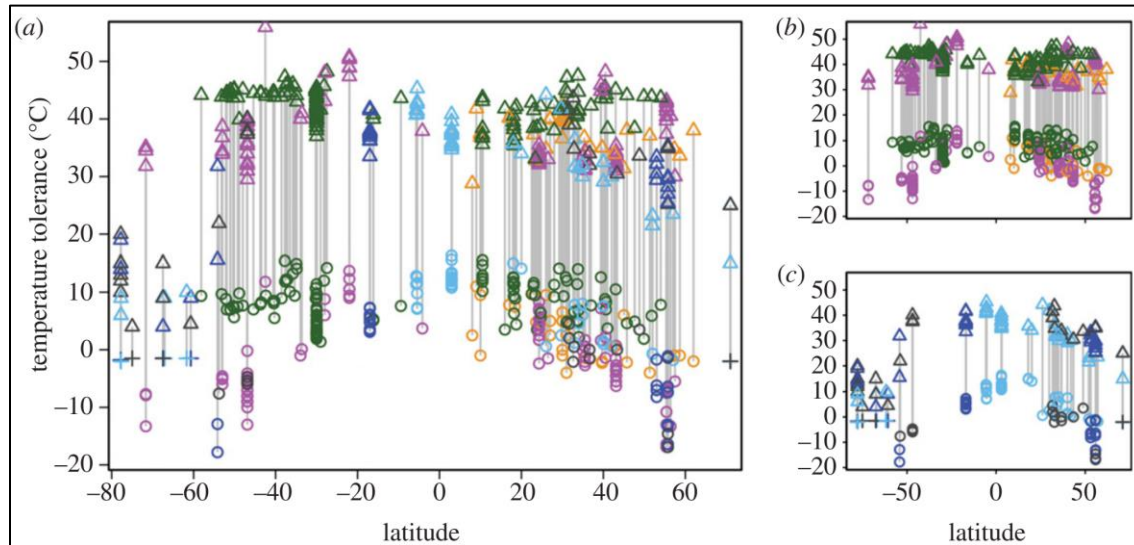


Figure 1. Variation of thermal tolerance limits of ectotherms across the world based on (a) taxonomic level, (b) terrestrial and (c) marine species; constraints also by latitudinal variation (Sunday et al., 2011).

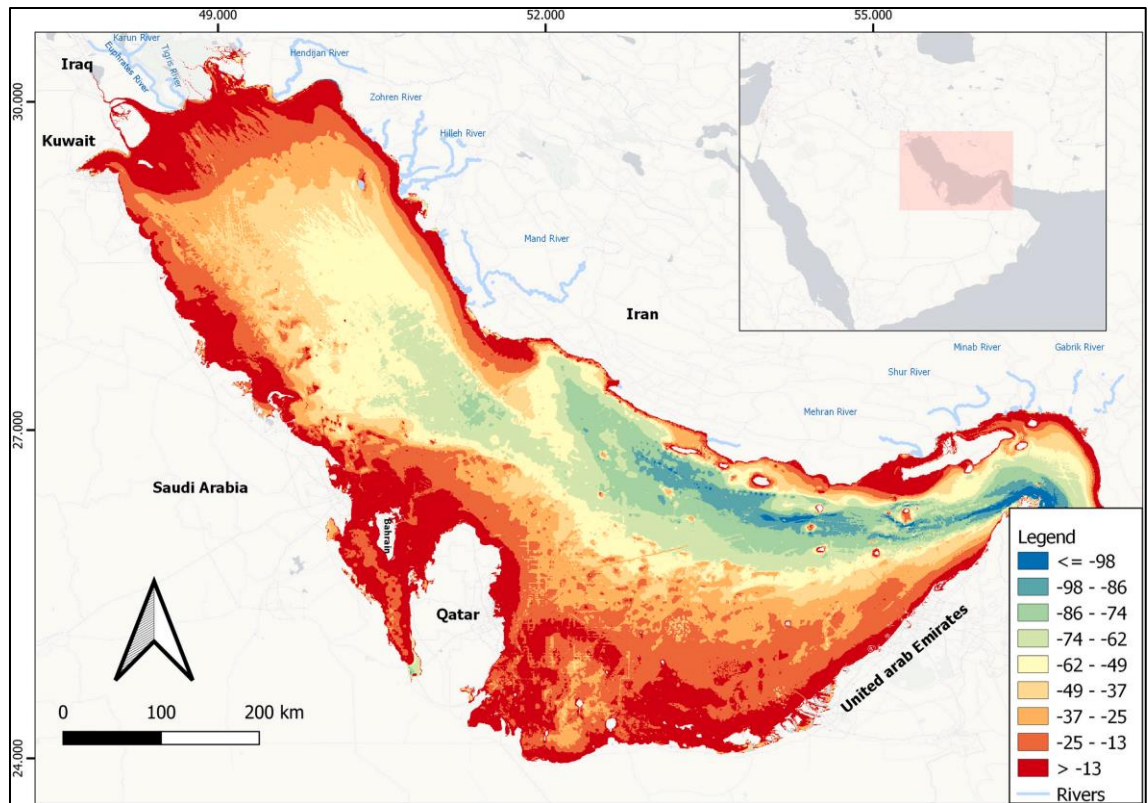


Figure 2 Bathymetric map of the Arabian Gulf (Amao et al., 2022)

In a broader view, the Arabian Gulf represents what we know as mixed system of carbonate and siliciclastic realms, where both of them occur side by side and have possible analogues towards the geological perspective (Riegl and Purkis, 2012; Amao et al., 2022). The occurrence of limited fluvial input that supplies sediment into the system is mainly found in the areas around active rivers on the Iraq and Iran side, especially in Shatt Al-Arab and the river system across the Zagros Fold Belt (Purser, 1973; Alsharhan and Kendall, 2003; Amao et al., 2022), supplying siliciclastic deposits within the surrounding region. This condition later triggers the deposition of siliciclastic sediment that mostly fine-grained, forming marl with elevating carbonate content away from the coastal area (Alsharhan and Kendall, 2003; Amao et al., 2022). On the other hand, the deposition of a carbonate system where influence of freshwater and sediment input that possibly interrupt the processes are limited also occurs elsewhere across the Arabian Gulf. The occurrence of a carbonate ramp,

reef-platforms, and carbonate hardgrounds in the intertidal area are common findings, especially in Saudi Arabia and adjacent areas, especially in the shallow water region (Purser, 1973; Weijermars, 1999a, 1999b; Amao et al., 2022).

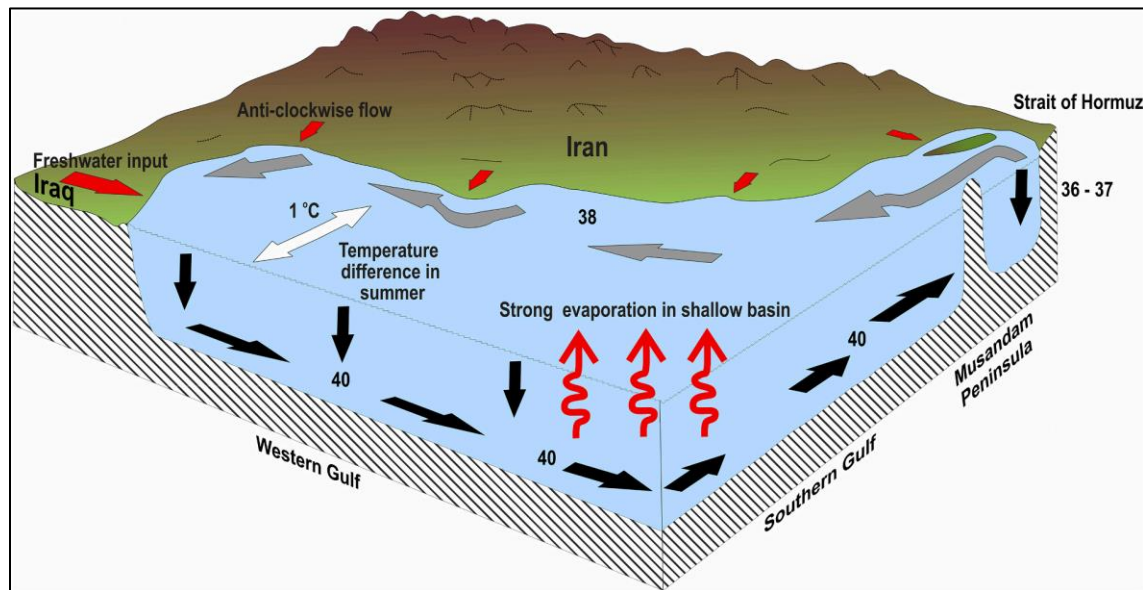


Figure 3 Schematic model representing moving flow of water within the Arabian Gulf, as well as interrelated processes and sea surface temperature across the region (Amao et al., 2022)

1.3 Benthic Communities Studies in the Arabian Gulf

Several studies related to the benthic communities in the Arabian Gulf have outlined some key points. There are four major findings or aspects (where some of them are partially answered or unanswered) related to the studies of benthic communities that already have a long journey, traced back originally from the middle of 20th century.

1.3.1 Diversity

As a basic understanding, an area with extreme environment (in the Arabian Gulf case this means high temperature and salinity), there is a limited number of communities that will develop and bloom into various assemblages (Rothschild and Mancinelli, 2001). These findings also supported based on study of macrofaunal such as mollusk and meiofauna

such as ostracods and foraminifera (Clarke and Keij, 1973), where compared to the open ocean, the diversity index of biota in the Arabian Gulf is considered impoverished. However, as time passes and a better understanding with support from sufficient equipment, major renewal of basis related to the diversity within the Arabian Gulf are being considered. For example, Cherif et al (1997) reported that only small quantities of foraminiferal taxa are found in the entire Arabian Gulf. On the other hand, the study by (Amao, 2016) reported within a small area of the Arabian Gulf, many more taxa are found, exceeding previous reports. Not only more various than past reports are being outlined, but also several new findings and even endemic species have been found in the Arabian Gulf, either already being named or under review for further consideration (Amao and Kaminski, 2016, 2017, 2019; Garrison, 2019; Kaminski et al., 2020).

1.3.2 Lateral Distribution

Not only aspects of diversity are being reported in general, but also how those benthic communities are gradually changes in their lateral distribution. The best example of how the gradual change of biota is properly observed is based on foraminiferal studies. Several studies are being conducted and based on proper sampling where the representation of lateral change from the coast towards the deeper part shows changing assemblages (Basson and Murray, 1995; Arslan et al., 2016a; Amao et al., 2018). From the coastal area, more porcelaneous-test and hyaline-test foraminifera, while the area further offshore contains more agglutinated-test foraminiferal assemblages (Cherif et al., 1997; Amao et al., 2018, 2022). In respect to the previous aspect, within the various salinity levels in lateral distribution, different assemblages of taxa can be found. For example, assemblages within

highly saline lagoons are quite different from the normal or lower salinity in the open Arabian Gulf (Amao et al., 2022; Gull, 2022).

1.3.3 Natural and Anthropogenic Threat

In order to further understanding the threat of natural and anthropogenic disturbance towards the benthic communities, several publications have been conducted but mostly on localized scale. Most of these studies investigated intertidal benthic biota such as mollusks that are contaminated with heavy metals and other hazardous constituents. Another group of organisms observed in relation to pollution are the foraminifera, with low diversity and dead assemblages dominating the systems (Arslan et al., 2016a, 2016b). Within the same aspect of foraminifera, the occurrence of abnormalities in foraminiferal test growth and morphology are found in the relatively unpolluted environment of the Arabian Gulf (Amao et al., 2016, 2018, 2022; Kaminski et al., 2021b). This very finding is later raising further question: what can possibly trigger their deformities observed in the Arabian Gulf?

1.3.4 Future Uncertainties

The uncertainties about what is likely going to happen in the future regarding benthic communities remain unanswered. Some scientists maintain that future climate change will trigger increasing temperatures across the Arabian Gulf (Shirvani et al., 2015; Pal and Eltahir, 2016; Safieddine et al., 2022; Figure 4), where the most highly impacted communities are the patchy corals that show bleaching or lose their symbionts over time (Coles and Fadlallah, 1991; Coles and Riegl, 2013; Paparella et al., 2019; Bouwmeester et al., 2020). Other effects are the impact of intensifying pollution in the Arabian Gulf that currently impacts animals such as mollusks and fish, where the other are remains unimpacted (Jawad, 2021). Not to mention some past events with possible future

occurrence of harmful events such as algal blooms (Al Shehhi et al., 2014; Al-Yamani et al., 2020) and oil spills (Verma et al., 2008; Danish, 2010; Amir-Heidari and Raie, 2018) that badly affect the Arabian Gulf in the past and the future possibilities of occurrence are remain under question. Rising salinities that also interrelated between climate-induced rising temperature with low precipitation within the Arabian Gulf will have high possibilities to significantly shift future biodiversity, either inducing more deformities (Geslin et al., 2000) or making the environment uninhabitable for some animals (Cacciapaglia and van Woesik, 2016; Dixon et al., 2022).

1.4 Research Gap

In order to understanding the physio-chemical influence towards the natural intertidal communities in the Arabian Gulf, we need to first take a look into which intertidal communities exist within our system. Several findings from many researchers explain that mollusks (either gastropods and/or bivalves), arthropods (mostly crabs and ostracods), annelids (worms), and foraminifera (calcareous- and agglutinated-test benthic) are of most concern. These studies mainly concern biodiversity or assemblages, while others concentrate on anthropogenic stressors within a polluted area. No significant study has addressed the direct impact of physical and chemical stressors in the unpolluted area across the Arabian Gulf, even for a small, constrained areas (small scale). Hereby, we place more concern towards exploring the physio-chemical constraints on intertidal communities in a small area of the western Arabian Gulf as a starting point, before expanding the study further into a wider geographical area.

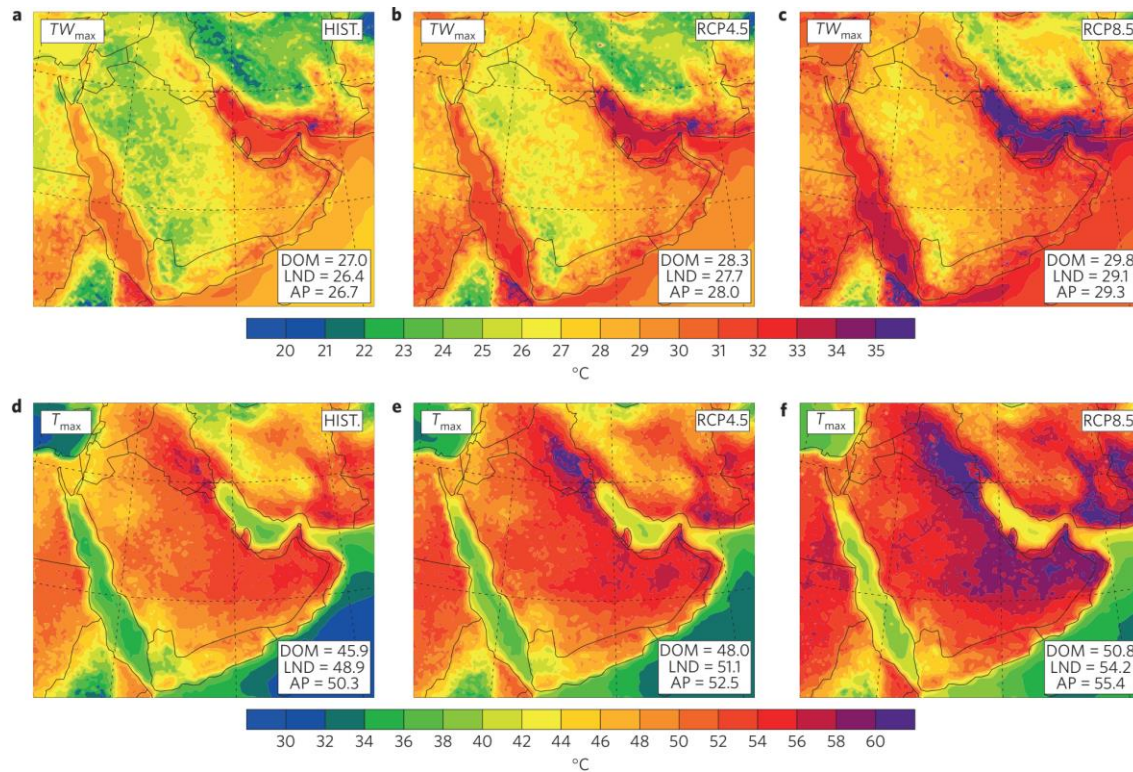


Figure 4. Various climate prediction model based on different scenario related to the extreme wet bulb temperature of the southwestern Asia region (Pal and Eltahir, 2016)

1.5 Objectives

The main objectives of this study are to build a deeper understanding about the impacts of various physical and chemical stressors towards selected intertidal communities in the western Arabian Gulf. In specific, this study aims to:

- 1) Identify the upper thermal limits of the selected intertidal communities, such as mollusks (gastropods), crustaceans (ostracods), and foraminifera (smaller and larger benthic foraminifera) under controlled conditions.
- 2) Quantifying the level of selected physio-chemical parameters such as temperature, salinity, trace metals (Mn, Cr, Cu, Ni, As, Pb, Cd, Zn, and Hg), organic constituents (total

organic carbon and total carbon) and the total assemblages of foraminifera with normal and abnormal/deformed morphologies.

3) Implementing appropriate statistical analyses for quantifying the assemblages of foraminifera (diversity indices) and correlating between the morphological deformities and the most influential physio-chemical parameters.

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CHAPTER 2

UPPER THERMAL LIMIT EXPERIMENT TOWARDS SELECTED LIVING INTERTIDAL-COASTAL BIOCALCIFIERS FROM WESTERN ARABIAN GULF AREA

*Submitted and accepted in Arabian Journal for Science and Engineering
(Ostracod Data); Submitted in Regional Studies in Marine Science
(Gastropod Data)*

2.1 Abstract

This study aimed to assess the resilience of biocalcifying organisms in response to projected ocean warming in the intertidal and lagoonal regions of the Arabian Gulf. We collected two representative animal groups with substantial population sizes: gastropods and ostracods, from two distinct locations in the western Arabian Gulf, one on the eastern coast of Bahrain and the other in Saudi Arabia. Specifically, we examined two gastropod species, the mud creeper *Pirenella conica* (Blainville, 1829) from Saudi Arabia's Half Moon Bay and the tropical periwinkle *Planaxis sulcatus* (Born, 1778), along with a salinity-tolerant ostracod species, initially identified as *Cyprideis torosa* (Jones, 1850) from Bahrain's Murray's Pool locality. We conducted thermal experiments by subjecting

these specimens to controlled conditions within a petri dish, replicating the natural environment based on different scenarios, and heating them in a thermal incubator for a duration of two to three hours, dependent on the scenario and specimen. Our findings indicate that both gastropods and ostracods have elevated upper thermal tolerance, particularly when immersed in water within the experimental setup. Additionally, some specimens exhibited distinct behaviors, such as varying recovery times after the experiment and partial immobility during the trial, though none displayed complete immobility. These results offer valuable insights into the resilience of intertidal-coastal biocalcifiers in the face of future warming uncertainties in the Arabian Gulf, shedding light on their potential thermal limits in the context of current ocean warming trends.

Keywords: thermal experiment, upper thermal limit, marine biocalcifiers, intertidal-coastal, Arabian Gulf

2.2 Introduction

The Arabian Gulf confronts significant environmental challenges amid the current backdrop of global warming. Notably, there is a surge in the frequency and intensity of coral bleaching events (Riegl et al., 2018; Burt et al., 2019), a phenomenon with far-reaching repercussions for marine ecosystems. Recent climate modeling research (Pal and Eltahir, 2016) foresees the region spanning from Qatar to Saudi Arabia as the area most profoundly impacted by forthcoming climate alterations, with projected wet bulb air temperatures surpassing 35°C, a lethal threshold for the majority of animal species (Sunday et al., 2011, 2012).

When considering the recent temperature challenges in the Arabian Gulf region, Saudi Arabia and Bahrain emerge as particularly vulnerable nations. Local reports from both

countries indicate a troubling trend of soaring temperatures over the last five years and the current year. Bahrain, in particular, has experienced record-breaking heat, with temperatures reaching an unprecedented 48.7°C in 2021 (Kunal, 2021) and consistently exceeding 40°C during the summer of 2023 (Meteorological Directorate Climate Section, 2023). Similarly, Saudi Arabia, especially in its eastern region, is facing the prospect of temperatures exceeding 50°C, given that observed temperatures have consistently ranged between 46°C and 48°C in 2023 (Abueish, 2023). This concern was also raised in the previous year, as areas like Dammam in the Eastern Province reported temperatures as high as 48°C (Hassan, 2022).

Despite alarming forecasts for the future state of numerous ocean ecosystems, including the Arabian Gulf (Pal and Eltahir, 2016; Wabnitz et al., 2018; Noori et al., 2019; Zittis et al., 2022), there has been a notable absence of experimental investigations into the thermal tolerance and lethal thresholds of intertidal marine fauna in the western Gulf. A recent study on intertidal and subtidal marine species in Singapore and Thailand has unveiled upper lethal temperature limits ranging from 41° to 52°C (Nguyen et al., 2011). However, it is worth noting that such temperatures are already routinely exceeded in the intertidal mudflats of Bahrain during the summer months (Kaminski and Garrison, 2020; Kaminski et al., 2021a). To enhance the accuracy of our predictions regarding the future of the biocalcifying marine benthos in the Gulf, it is imperative to conduct laboratory experiments aimed at determining the lethal thresholds of organisms inhabiting shallow marine environments.

In a survey of macro- and meiofaunal organisms conducted during the summer of 2019 (Kaminski et al., 2021a), the presence of a "dead zone" was observed in the upper reaches

of the intertidal zone in Murray's Pool, where surface substrate temperatures exceeded 52°C in summer. Conversely, in the Saudi Arabian counterparts, summer temperatures can soar to levels exceeding 55°C, particularly in the seasonal pools during low tide. Furthermore, maximum substrate and water temperatures, as recorded by in-situ temperature monitors, exhibit significant daytime fluctuations within a one-hour interval (Kaminski et al., 2021a). In Murray's Pool, living meiofaunal organisms were exclusively sighted in the tidal channels and permanent pools during the summer months where salinity ranged from 43 to 47 PSU (Amao et al., 2016; Amao, 2016), with ostracods being notably abundant. In contrast, meio- and macrofaunal assemblages in the seasonal pools of the Saudi Arabian locality thrive in salinities exceeding 60 PSU. This study aims to determine the thermal tolerance of biocalcifying organisms, namely gastropods and ostracods, which are primary contributors to the region's living biota. The objective is to make predictions about the potential impacts of climate change on shallow-water marine biocalcifying organisms in the Gulf region. To our knowledge, there is no comparable contemporary study that comprehensively assesses upper thermal limits for both types of organisms, both regionally within the Middle East or on a global scale.

2.3 Study Site

Our study involved the monitoring of two specific locations within the western Arabian Gulf area: a small lagoon on the eastern coast of Bahrain, subject to thermal stress during the summer months (Kaminski and Garrison, 2020; Kaminski et al., 2021a), and another seasonal pond situated in the southwestern region of Half Moon Bay in Saudi Arabia (see Figure 5). Until recently, the Bahraini site remained the sole location within the Kingdom of Bahrain where foraminiferal investigations had been conducted (Basson and Murray,

1995; Amao et al., 2016; Arslan et al., 2016a), while in the case of the Saudi Arabian site, comprehensive foraminiferal studies were absent, with limited macrofaunal research pertaining to environmental considerations. Both seasonal lagoons exhibit distinct faunal assemblages and provide habitat to a diverse array of marine organisms and wading birds, particularly in the Bahraini part (Al-Sayed et al., 2008). In contrast, the Saudi Arabian lagoon accommodates a limited number of biota assemblages, especially living biocalcifiers (Kaminski et al., 2023). Periodically, satellite imagery from Google Earth documents flood events due to elevated tides, with specific times of the day illustrating these occurrences in both lagoons or pools (see the attribute from the map in Figure 5). Dark patches seen in the maps represent wet areas that inundate during high tide and subsequently desiccate over the course of the day.

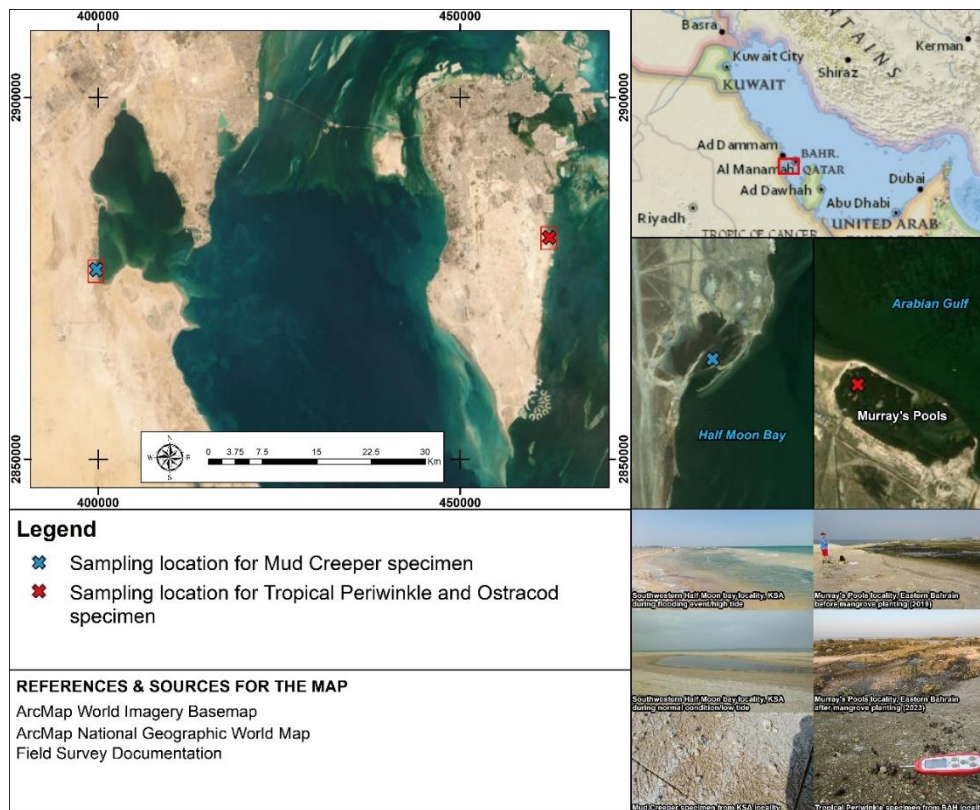


Figure 5. Map of the sampling locality for the specimen used in our experimental works

Numerous prior studies (Amao et al., 2016; El-Sorogy et al., 2016, 2019; Kaminski et al., 2021a; Nazeer et al., 2021; Joydas et al., 2023) have examined the benthic marine communities in these regions, encompassing various organisms such as mollusks (gastropods and bivalves), arthropods (crabs and ostracods), annelids (nematodes), and foraminifera. Moreover, we consider both study locations as among the last remaining natural sanctuaries for intertidal marine communities in the vicinity, in light of the rapid human development along the coastlines of Bahrain and the Saudi Arabian sector of the Gulf.

Bahrain and Saudi Arabia's intertidal areas exhibit several shared characteristics. Kaminski et al. (2023) documented a noticeable temperature gradient spanning the intertidal zones from the foreshore to the lagoon. This gradient persists throughout both winter and summer seasons. Field measurements have shown that temperatures within the intertidal areas can dip as low as 17°C during the winter months (December to February) and soar beyond 60°C during the summer (May to August). In the summer, gastropods tend to avoid mudflat areas where temperatures exceed 40°C (Kaminski and Garrison, 2020). The frequency of substrate exposure, as well as the presence of marine organisms residing above or below the substrate, is influenced by the tides and wave heights, alongside the seasonal solar insolation-driven temperature constraints. Periodic breaking waves and high tides introduce water into the lagoons, only for these same lagoons to subsequently dry up, leaving marine organisms exposed to heightened temperatures and diminishing water pools. These creatures must demonstrate adaptability and resilience to survive within three distinct environmental scenarios: (a) complete exposure during low tide or when no water is present in the lagoon or pools (full exposure or FE), (b) partial exposure as the water

begins to recede (partial exposure or PE), and (c) complete submersion during high tides (full coverage or FC). Moreover, it is noteworthy that salinity levels in Murray's Pool are significantly lower than those in Zabnah Beach Lagoon, with values ranging approximately from 45 to 47.5 PSU versus 70 PSU, thereby contributing to the physio-chemical distinctions between the two areas.

2.4 Materials and Methods

2.4.1 Specimen Selection and Sampling for Experimental Works

To address the need for assessing temperature adaptability under varying intertidal conditions, we chose two distinct species, each exemplifying one of the three scenarios in the intertidal habitat. The tropical periwinkle, scientifically known as *Planaxis sulcatus* (Born, 1778), and the mud creeper, *Pirenella conica* (Blainville, 1829), were selected to represent intertidal gastropod species in our study. These species not only exhibit characteristic body and shell shapes but also possess distinct ecological preferences (Smythe, 1982). The common periwinkle, *Littorina scabra* (Linnaeus, 1758), and the tropical periwinkle both feature a smooth shell surface, a prominent body whorl that rapidly expands in diameter as they mature, and a low trochospirally coiled shell. In contrast, the mud creeper has elongated and narrower shells (over 30 mm for an adult), with a twisted columella and spiral beaded rows. Notably, in Murray's Pool, where both tropical periwinkles and mud creepers are abundant, the former tend to aggregate and either adhere to rocks or construct pyramidal structures as part of their seasonal thermoregulatory behavior, a phenomenon not observed in mud creepers (Kaminski and Garrison, 2020). Conversely, recent observations have not identified tropical periwinkles in the Half Moon Bay area.

Specimens were collected in the morning, placed in a plastic container, and promptly transported to the KFUPM Laboratory of Micropaleontology to initiate the next phase of the experiment. From the numerous specimens previously gathered, six were randomly selected and housed within a 100 mm diameter petri dish equipped with a lid to maintain moisture. Three distinct scenarios were established to replicate the typical substrate and environmental conditions found in their natural habitats. These scenarios allowed the snails to interact with the substrate through grazing or feeding mechanisms. The scenarios included (a) complete immersion in lagoon water at a specific depth, (b) partial exposure to lagoon water, and (c) full-body exposure on wet mud. Divided into three groups, a total of 18 snail specimens were employed for each experimental trial (approximately 200 specimens were used in total).

Contrary to the gastropod's specimen, living ostracods were collected only from the farthest section of Murray's Pool, which is distal from the tidal channel inlet (see Figure 5). The initial collection took place in August 2022, with additional sampling conducted in April 2023 for replicate trials. To gather sediment samples, an open sample jar was dragged along the surface of the pool's bottom mud. Temperature measurements were recorded in situ using a thermometer probe (TAYLOR RA44069 806GW Digital Thermometer), with an accuracy of 0.1°C. Both sediment and water samples were promptly transported to the Micropaleontology Laboratory at King Fahd University of Petroleum & Minerals (KFUPM). Ostracods were carefully separated using a fine brush and placed in a glass petri dish containing water from the sampled pool, characterized by a temperature of approximately 20.1°C and a salinity level of around 46.5 PSU. Only living ostracods displaying signs of movement were selected for the experiment. To ensure that no

specimens were immobile or deceased before the commencement of the experiment, composite images were captured, documenting the pre- and post-experiment positions of the specimens using a Leica S9i Digital Stereo Microscope. All specimens examined belong to the *Cyprideis* genus. Given the lack of taxonomical studies on these specimens in our current locality and their specific external morphological characteristics, we designate them as *C. sp.*, in accordance with the genus as presented by (Schön et al., 2017) in their plate's materials.

2.4.2 Upper Thermal Limit Experiment Procedures

A number of requirements relating to the thermal experiment or a basic ecological-related works need to be met in order to produce a proper ecological experimentation (Hairston, 1989). These requirements include having knowledge of the initial conditions, sufficient controls within the experiment, and adequate replication. Our thermal experiment for both type of specimen was conducted in two duplicate sessions at one temperature interval in order to comply with these requirements, with the actual environmental parameters at the field station where the specimens were sampled already specified. An attempt to mimic the actual condition such as the living substrate usage were employed, especially for the gastropod specimen, as well as the different field scenario within the following explanation below.

In the case of gastropod specimens, we endeavored to recreate the three natural scenarios within laboratory settings using petri dishes. In the first scenario, which entails full exposure to wet mud, we introduced local sediment to a depth of about 3 mm inside the petri dish. This previously compacted silt was then covered with approximately 10 cc of lagoon water to replicate the damp, moist mud conditions. In the second and third

scenarios, we employed the same amount of sediment in the petri dish but varied the quantity of water added. For the second scenario, approximately 25 ml of lagoon water was introduced, extending about 0.3 cm above the sediment. In the third scenario, we added 50 ml of water to the petri dish with the 0.3 cm thick sediment, creating a water depth of roughly 0.6 cm above the sediment. Figure 2 illustrates the arrangement of the petri dish for the experimental scenario in our study, while Figure 6 depicts the configuration of the petri dish for placing the snails and monitoring their movement. Overall, our experimental approach deviated from the prior studies on temperature limits, which were first introduced by Evans (1948) and subsequently revisited in numerous similar methodologies, as seen in the other following works (Stirling, 1982; Williams and Morritt, 1994; Davenport and Davenport, 2007; Han et al., 2019; Li and Dong, 2020) conducted experiments most closely aligned with our methodology, involving a range of settings and heat exposures in gastropod species.

The snails were subjected to controlled heating using a Memmert Universal Oven U Incubator I UN 30 series with precise temperature control. For the heating experiment, multiple snail specimens were placed in petri dishes designed to mimic natural substrate and exposure conditions. These specimens were exposed to five different temperature levels (40°C, 45°C, 50°C, 55°C, and 60°C), with replicates to ensure the reliability and consistency of our results.

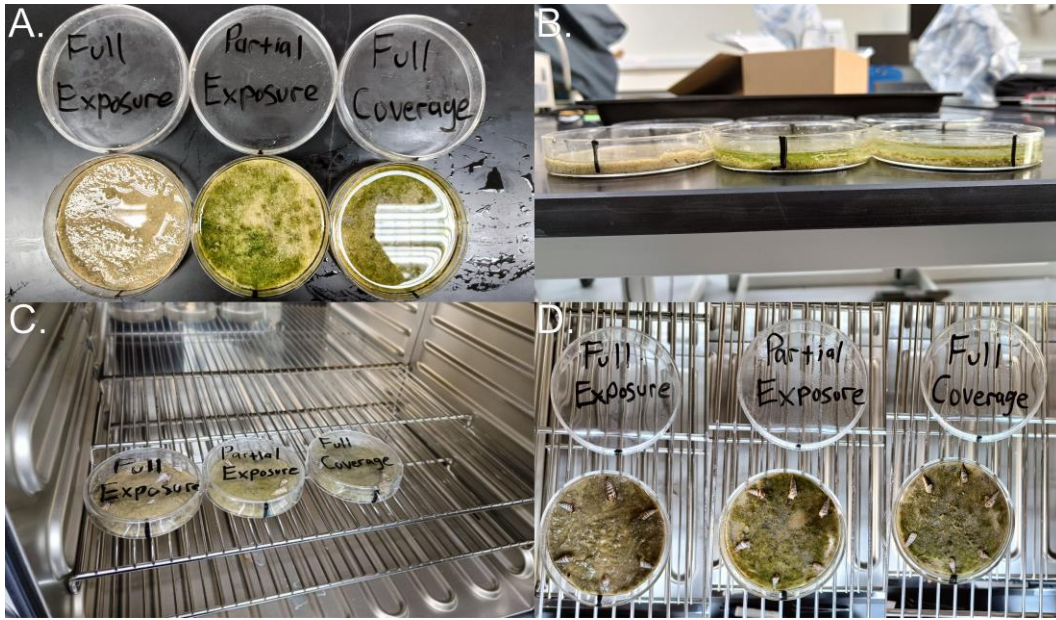


Figure 6. Experimental setup for the heat exposure trial: A. vertical overview of the substrate, B. lateral overview of the substrate and water coverage, C. configuration of the materials inside the incubator, and D. specimen setup inside the petri dish.

Three sets of petri dishes, each representing one of the three environmental scenarios, were simultaneously placed into the oven in a specific order. Before the experiment's commencement, we recorded the temperature of the substrate in the petri dishes and the initial specimen placement to establish a starting point and a reference for subsequent measurements. Each petri dish accommodated a specimen placed in one of six positions, with the anterior canal oriented toward the center and the shell's apex either in contact with or very close to the dish's rim. We used a TAYLOR RA44069 806GW Digital Thermometer to measure the substrate temperature within the petri dish, inserting the instrument's tip into the substrate surface. For each step, we captured three images of each petri dish, showing the specimen's current position and condition, along with real-time readings of the substrate temperature.

During the thermal exposure experiment, which lasted three hours, three procedures were conducted: two pre-exposure (Figure 7) and one post-exposure procedure. Direct

observation during thermal exposure was not feasible due to equipment limitations; therefore, regular specimen checks were performed at specified intervals. The initial placement, the first procedure, occurred as the petri dish containing the specimen and the water-sediment mixture was introduced into the oven. The second procedure, initial heating, commenced between the recorded temperature during the initial placement and the desired air exposure temperature within the system. The heating interval was set 10°C below the intended exposure temperature, e.g., a 40°C exposure would begin when the air temperature inside reached 30°C. Temperature measurements were taken during the initial step and each specimen observation session to assess the temperature difference between the two.

Subsequently, the primary heat exposure technique was conducted twice, each with a distinct duration, once the air temperature reached the desired target. During a one-hour experiment, the first interval was used, with five-minute intervals between observations, documentation, and recordings. The subsequent round of primary experiments spanned two hours, with a 10-minute gap between data collection sessions. In either the first or second batch of experiments, a total of 27 data recordings, 27 sets of photographs for each petri dish (81 in total), and 27 substrate temperature measurements for each dish (81 in total) were obtained. These measurements were taken once for each recording, representing the three different scenarios, and later repeated as a replicate experiment to serve as control data for the main experiment.

The third step involved allowing the specimens to recover in new petri dishes filled with fresh water after their removal from the experimental petri dish. The time it took for each specimen to recover or reawaken following the experiment was documented during the

recovery observation, providing insights into the duration of heat-induced unconsciousness experienced by each specimen after the final phase of the experiment.

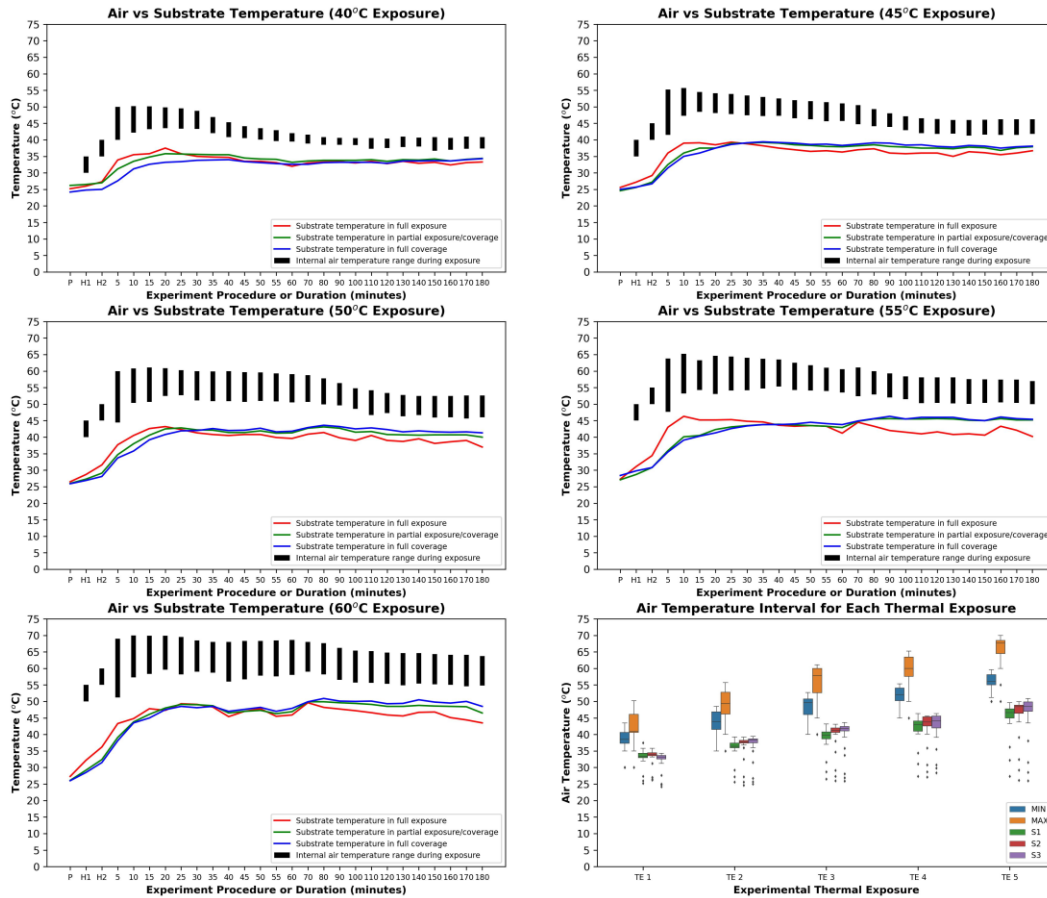


Figure 7. Line and boxplot graph representing temperature fluctuation during the course of thermal experiment between different heat exposure

For the ostracod specimens, the petri dish containing 30 specimens of living *Cyprideis* sp. was placed in an incubator (Memmert Universal Oven U Incubator I UN 30) initially set at 30°C. The ostracods' reactions to heating at specific time intervals and temperature ranges were observed in this study, using different specimens and stages of temperature increase (one set of specimens for each experiment course). In the main experimental scenario, the petri dish containing the ostracods was heated with a 5°C temperature increment and exposed for 10 minutes before proceeding to the next temperature value,

with the first measurement commencing at 30°C air temperature and 10 stages of temperature increase with 5°C increments. In this scenario, the air temperature inside the incubator reaches the targeted level at various intervals until the temperature indicator blinks as representing stabilized internal air temperature, but the air temperature does not represent the water temperature inside the petri dish (which is lower than the air temperature inside the incubator due to water's heat capacity). After each time interval, the temperature values of the water of each end-to-end of a 10-minute time interval was measured using a portable probe thermometer (TAYLOR RA44069 806GW Digital Thermometer), with an accuracy of 0.1°C. Figure 7 presents the air temperature in the incubator and the water temperature in the petri dish in the main experiment and replicate experiments.

2.4.3 Behavioral Observation towards the Used Specimen

In addition to the thermal experiment that we conduct, we also observe the typical trait behavior that our specimen experience and exhibit during and after the experiment. In this way, we are able to foretold which specimen that remain alive during or after the experiment, and which one that die afterwards. For the gastropod specimen, along with the experiment process, we observe the typical behavior that our specimen during the heat exposure intersession, as well as recording their current status. For each image being taken every intersession, we compared between previous position to current position, to consider that our used specimen was alive at the observation and recording time. Each representative image was used to compare which specimen that still alive during the current recording, as being seen in the Figure 8 previously.

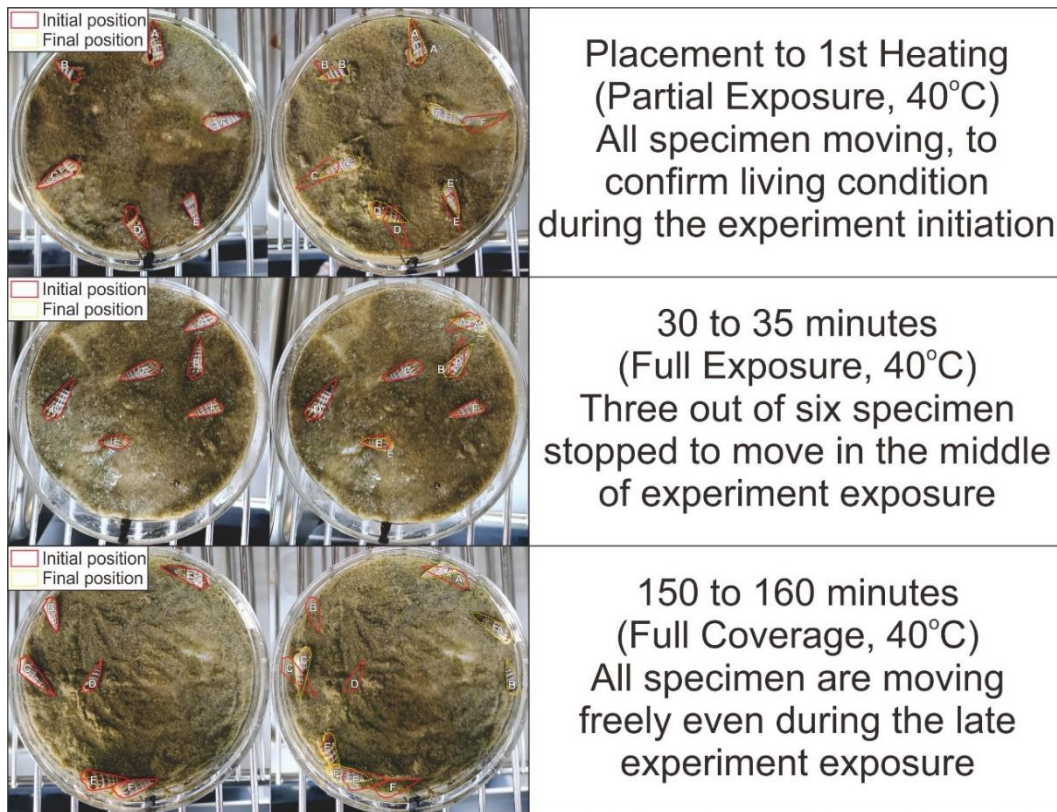


Figure 8. Visual observation on how the specimen behave like movement from one part to another between two different time observation, temperature exposure, and scenario.

At the culmination of each 10-minute exposure interval within the incubator experiment, we evaluated the state of our specimens by assessing their mobility (agile or sluggish), as well as their activity level (active or sedentary). Up to five minutes of recovery time were added after observations at room temperature outside the incubator chamber in order to establish the temporary conditions of our specimens before moving on to the next higher temperature exposure while observing their actual condition and behavior using an Olympus SZX7 Stereomicroscope. Due to technical limitation in our study, it was not possible to directly observe when the specimens stop moving or simply behave and reacts during heating within the incubator. The immobile specimens were later separated from the moving ones and when none of the test subjects moved after the five-minute recovery period and applying direct stimulus to their body parts (such as their legs) using a needle,

the ostracods were assumed to be dead, and the experiment was declared finished. A longer waiting period up to one hour was established for the end-stage experiment to confirm that all of the specimens were dead (when no specimen was observed to move after the final exposure interval). To document the visual death condition, we captured the post-mortem image the next day upon termination of the previous experiment, in addition to confirm that specimens were truly dead after one day post-experiment.

In addition to abovementioned part, to determine at which temperature our gastropod and ostracod specimens enter a coma, whether partially or completely within quantity basis, we recorded their status changes along with the temperature measurement. We determined the heat coma temperature (HCT) to represent when at least one of our specimens from each scenario entered a coma. Furthermore, we also determined at which temperature our half of our specimens experiencing become inactive or enter a comatose state, called the median heat coma temperature (CT50), as well as for all of the specimens becoming inactive, called the upper heat coma temperature (CT100). In the case of ostracod specimens where no individuals returned to life, we assigned the specific temperature as median lethal temperature (LT50) where half of the individuals are unable to regain consciousness, and upper lethal temperature (LT100) where the all of the specimens died or not regain consciousness after the recovery period ended.

2.4.4 Data Visualization

For all of the acquired data: the substrate temperature, number of specimens that shows status change, as well as temperature fluctuations during the experiment are processed using Spyder (Anaconda3). Different supporting package from the abovementioned software such as for data extraction and array-based data frame operation by using pandas,

mathematical function and operation by using numpy, and data visualization like generating representative graph by using matplotlib.pyplot for line graph and seaborn for boxplot graphs. Several graphs were adjusted into one single figure to represent as comparison by using subplot option from matplotlib.pyplot.

2.5 Results

2.5.1 Thermal Limit Experiment for the Gastropod Specimen

The mud creeper (*Pirenella conica*), the initial species investigated in this study, displayed distinctive responses to thermal exposure across different scenarios. In the first scenario, where the specimens were exposed to open air, the onset of limited mobility and entry into a comatose state occurred at 31.6°C. Subsequently, as the temperature continued to rise, at approximately 37.5°C, half of the specimens entered a comatose state, and at around 39°C, all individuals became immobile. Comparable outcomes were observed in the second scenario, with partial substrate coverage. However, in this case, the critical temperatures were higher, at 39.1°C, 44.8°C, and 48°C, signifying the initiation of comatose states, half of the specimens entering such a state, and the complete immobilization of the population. The third scenario, characterized by full substrate coverage, revealed higher temperature thresholds for each of these instances. At 45°C, 47.6°C, and 48.5°C, specific proportions of test specimens entered a comatose state. Notably, the first and second scenarios, as depicted in Figure 9, exhibited a gradual decline in recorded activity as the temperature increased during the experiment. In contrast, the third scenario demonstrated a sudden and pronounced decrease in the activity of the test specimens. These findings, based on five distinct temperature exposures and one duplicate trial for control (performed in duplicate), were averaged across the entire experiment and are summarized in Figure 10.

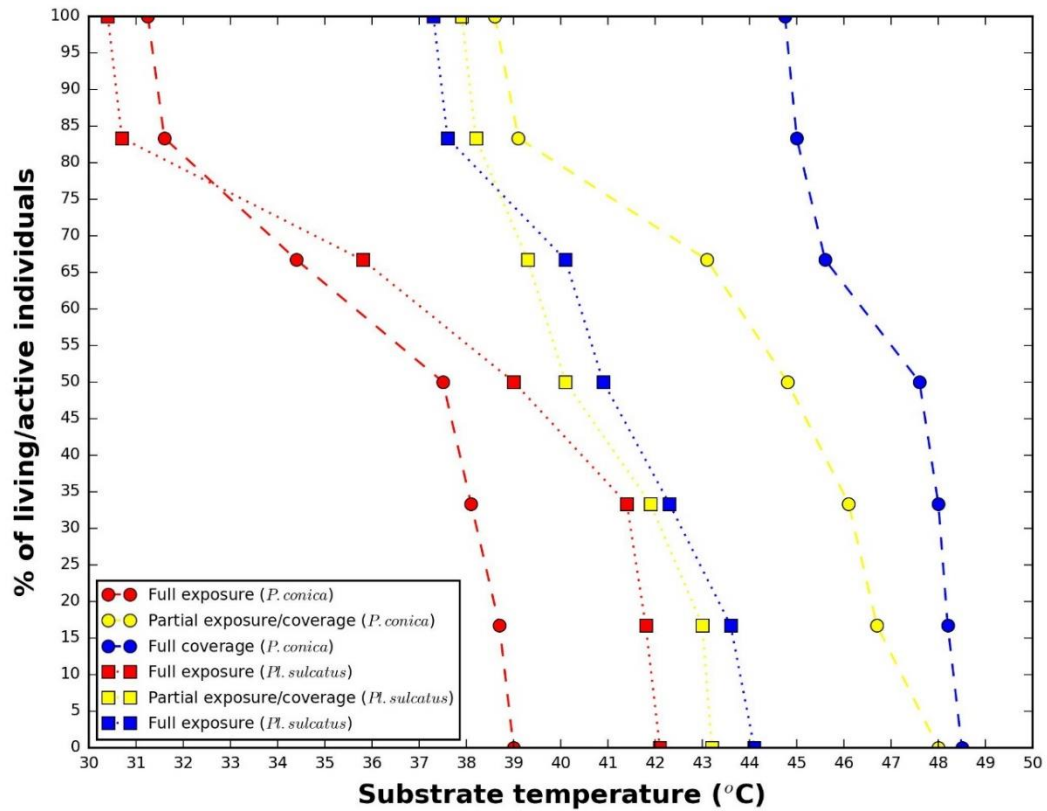


Figure 9. Overall result of thermal limit experiment, showing the HCT, CT50, and CT100 for each scenario, species, and temperature.

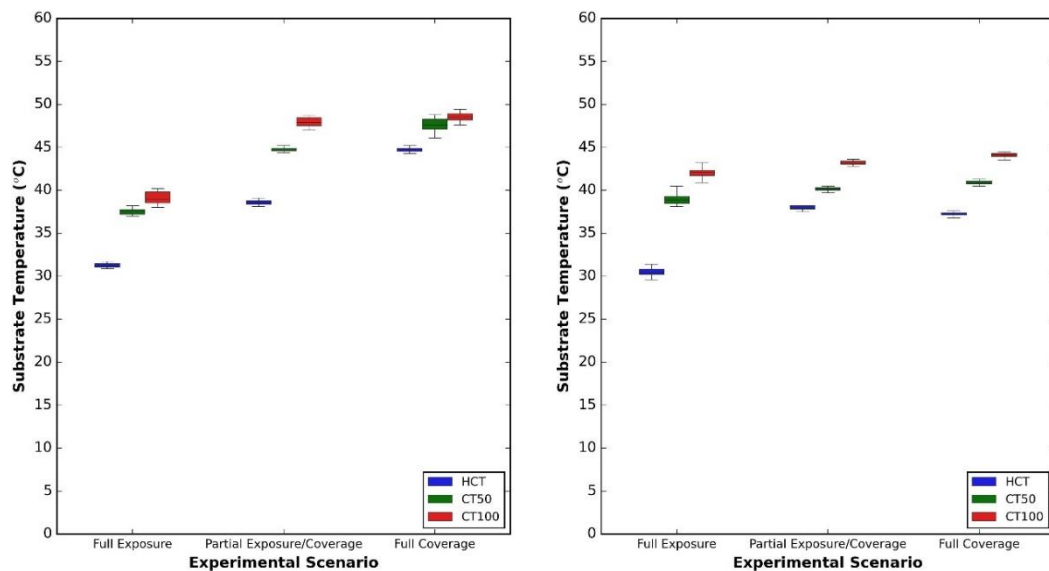


Figure 10. Detailed temperature range for each gastropod species in different case of comma temperature from different scenario exposure.

In contrast to the mud creeper, the tropical periwinkle (*Planaxis sulcatus*), an intertidal snail native to Bahrain, exhibited notably distinct outcomes, as depicted in Figure 9. This species displayed initial signs of partial immobility in the first scenario at a lower temperature compared to the mud creeper, specifically at 30.7°C. As the temperature continued to climb, the test specimens progressively lost mobility, with approximately half entering a comatose state at around 39°C, and all individuals becoming immobile at approximately 42.1°C. Generally, this species demonstrated a consistent decline in activity in the other two scenarios, which primarily differed in temperature thresholds. In both the second and third scenarios, the first specimen entered a comatose state at temperatures ranging from 37.6°C to 38.2°C, followed by half of the specimens experiencing immobilization between 40.1°C and 40.9°C, and ultimately, the entire test population became immobile at 43.2°C and 44.1°C, respectively. Comparing the three scenarios for this species, it became evident that the first scenario exhibited a gradual decrease in activity followed by a rapid decline, whereas the second and third scenarios witnessed sudden drops in activity as the temperature increased. Similarly, the results for the second specimen were obtained from five distinct exposure conditions, with an additional duplicate for control purposes, and are summarized in the boxplot graph presented in Figure 10.

2.5.2 Thermal Limit Experiment for the Ostracod Specimen

In our investigation, we found the initial thermal effect on the specimens (the HCT) for ostracod began representing at least one specimen entering comatose state (not dead) at 39.3°C; CT50 occurred around 46–47°C (no record for the 50% comatose status during experiment); and the CT100 was observed at 47.9°C. Additionally, within our observation, the initial lethal effect on the specimens began around 47.2°C; LT50 occurs around 51.8°C,

and the ULT was observed around 53.5°C. Survivorship curves of the specimens are shown in Figure 11. All of the number abovementioned is based on the average of main experiment and control, determined by calculating data between main experiment and control experiment.

2.5.3 Syn- and Post-experiment Behavioral Observation

Between both used specimen type (gastropod and ostracod) shows significant syn- and post-experiment behavior. For the gastropod case, regardless of the environment they are in during recovery, both species show a minor variation (Figure 12). The mud creeper's total recovery period varied from 18 seconds after exposure to 40°C the FC scenario, which was the shortest timeframe, to 90 seconds the FE scenario before the first specimen started moving again. The tropical periwinkle, on the other hand, exhibits somewhat longer initial specimen recovery time, with the lowest interval being roughly 42 seconds for the FC scenario and the longest being 102 seconds for the FE scenario. However, for the fourth heat increment (55°C), the mud creeper had the shortest recovery time, with the first specimen becoming mobile after 342 seconds, while the tropical periwinkle took 456 seconds to recover. Following the last heat treatment (60°C heat exposure), no specimens of either species showed any signs of recovery.

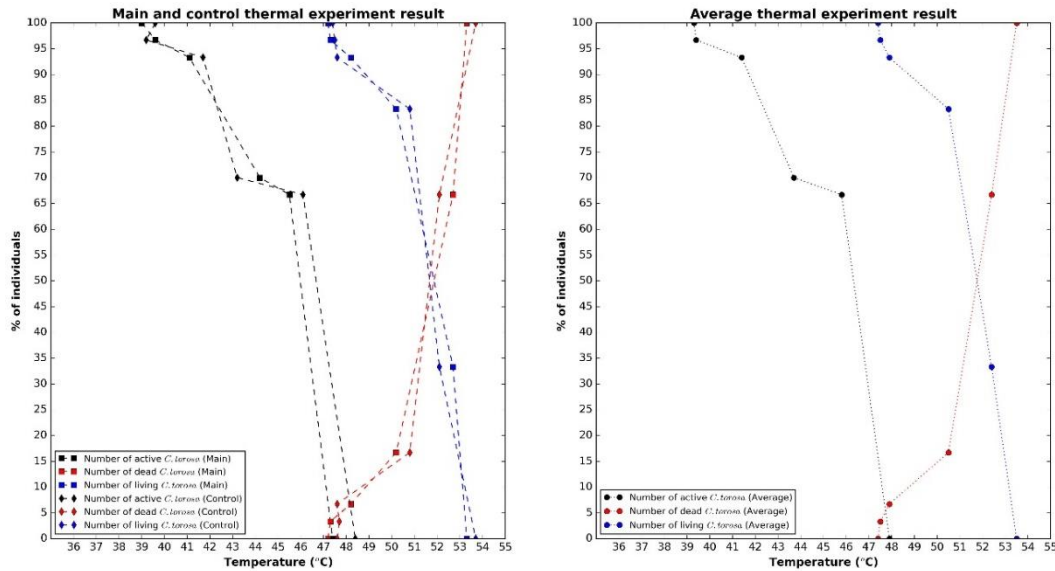


Figure 11. Overview of thermal limit experiment result for ostracod from two discrete experiment (main and control).

For the ostracod specimen, within the Figure 11, the number of specimens fluctuates as their mobility is observed and their current status is determined. For example, between 39.3 and 47.1°C, specimens are momentarily immobilized or enter a comatose condition, but later regain consciousness and start to show signs of life during the observation. This is the difference between ‘active/moving’ and ‘living’ status in Figure 11. On the other hand, above 47.2°C, some specimens were motionless even after the waiting time, hence their status was changed in the graphs from living to dead. The observed behavior of our specimens during the comatose condition consisted of temporary body part immobility during which their carapace is widely open, and therefore the animals are not protecting themselves from the short-term environmental stress such as salinity changes, oxygen stress, and aerial exposure with possible heat inducement (Athersuch et al., 1989).

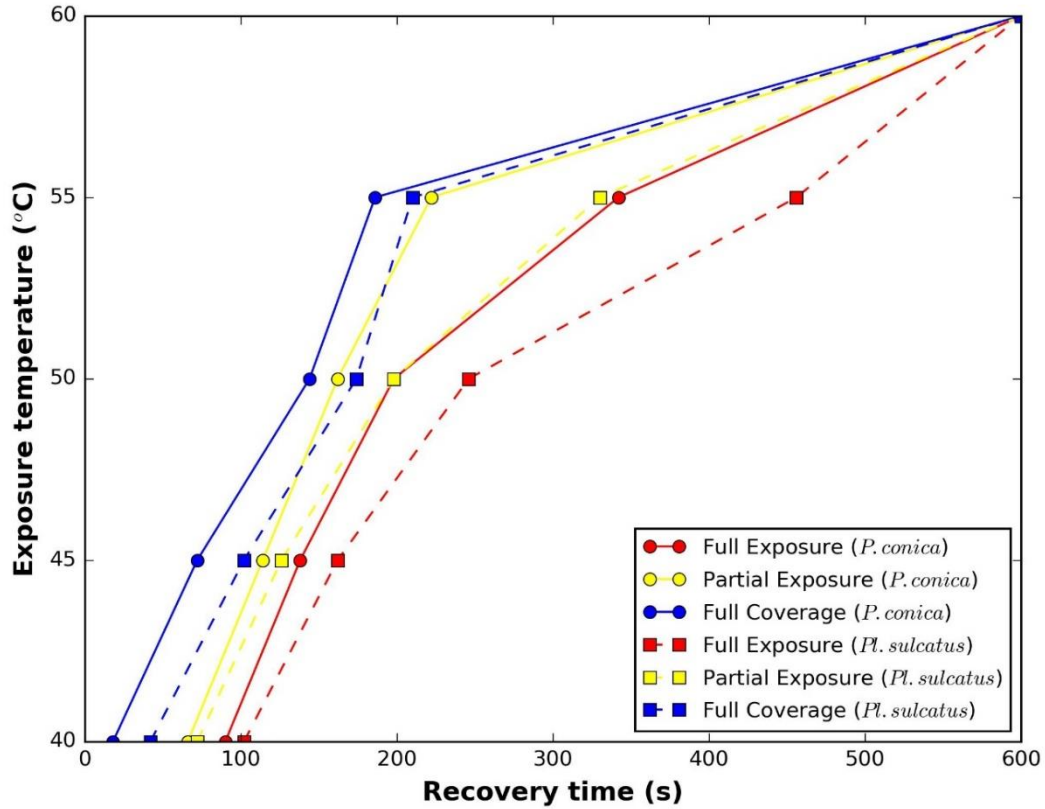


Figure 12. Line graph representing the recovery time for the gastropod specimen during the post-experiment session from each scenario and both species.

2.6 Discussions

Over the past five decades, extensive research has been conducted worldwide on the temperature tolerances of various mollusks, particularly gastropods, utilizing diverse analytical methods (Stirling, 1982; Williams and Morritt, 1994; Muñoz et al., 2005; Han et al., 2019; Mardones et al., 2021). However, limited attention has been given to the temperature limits of the Potamididae, or mud creeper gastropods, and the tropical periwinkle (Planaxidae), the focus of our study (Egonmwa, 2006; Nonyukela et al., 2019; Li and Dong, 2020). Despite their widespread distribution across the Indian Ocean, Arabian Gulf, and the entire Mediterranean, as documented in <https://www.marinespecies.org/>, there have been no specific studies conducted in the arid and hypersaline environment of the Arabian Gulf, our region of interest. The inhabitants of this region are exposed to one

of the most challenging environments on Earth, characterized by extremely high and fluctuating temperatures, physiological stress due to high salinity, and human-induced stress from oil spills and other types of pollution (Sheppard et al., 2010; Amao et al., 2019). Conversely, there is a substantial gap in our knowledge concerning shallow-marine ostracods in the western Arabian Gulf region, particularly with respect to their thermal tolerance. While studies have investigated the taxonomy and presence of marine ostracods in various regions, including the Iranian sector of the northwestern Gulf, southern Iraq, Kuwait Bay, and Abu Dhabi's lagoon, no comprehensive investigations have been carried out in Bahrain. Although the presence of living ostracods in Murray's Pool during summer was mentioned previously, there were no details regarding taxonomy or specific species identification (Kaminski et al., 2021a). Our research identified the ostracod species inhabiting Murray's Pool as belonging to the genus *Cyprideis*. This species shares similarities with *Cyprideis torosa* (Jones, 1850) (see Figure 13), characterized by similar valve morphology, smooth hinge, and external sensillia extruding from the carapaces. *Cyprideis torosa* is a euryhaline species with a broad geographical distribution, potentially carried by migratory birds along their routes (Wouters, 2017). This species has been reported in studies conducted in various locations, such as the Mediterranean, Greece, and the Arabian Gulf (Mostafawi, 2003; Wouters, 2017).

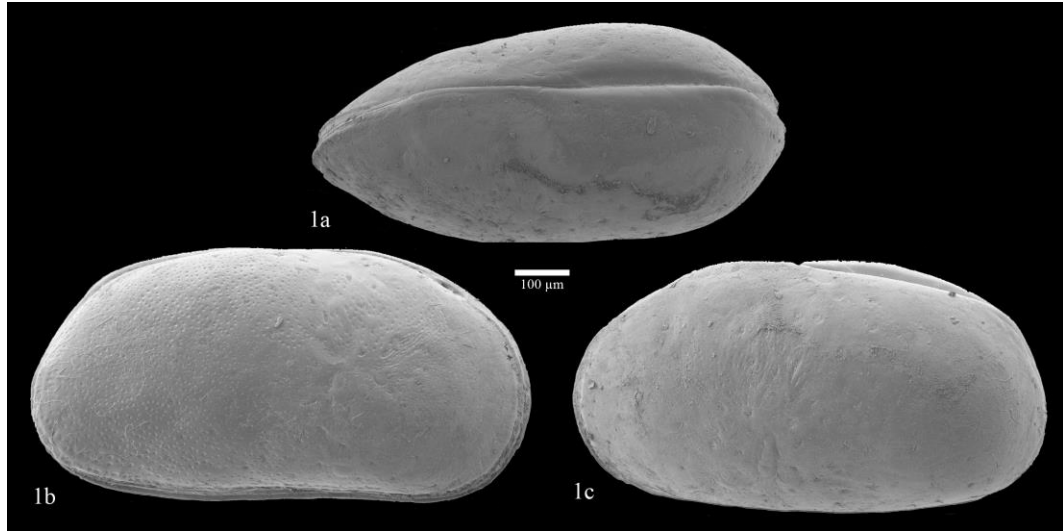


Figure 13. SEM images of the used specimen of intertidal salinity-tolerant *Cyprideis* sp.

Our experiments revealed that both gastropod species and the ostracod species exhibit distinct thermal tolerances to heat exposure. As logically indicated and corroborated by (Kaminski and Garrison, 2020), all specimens of both gastropod species entered a comatose state and became immobile when subjected to a substrate temperature exceeding 40°C. This is consistent with the field observations of a discernible "snail line" on the natural tidal flat during summer, where only dead snail shells are found in areas where the substrate temperature exceeds 40°C. Our FC and PE scenarios aimed to replicate these natural conditions in a laboratory setting. Notably, a higher thermal tolerance was observed in the FC scenario, where specimens were fully immersed in water. In the case of the tropical periwinkle, half of the specimens remained mobile at 42°C, whereas the mud creeper displayed a higher tolerance, with half of the specimens becoming immobile at 47.6°C. Li and Dong (2020) noted a similar trend in their experiment with gastropods from the same family, showing thermal limits in the range of 46°C to 48°C. Stirling (1982), in an acute lethal temperature experiment on marine gastropods from Hong Kong and Tanzania, reported higher thermal limits, with values of 56.5°C. However, it is essential to

note that Stirling's study did not consider substrate temperature as the baseline for thermal exposure, only accounting for heat induced from the water bath when determining thermal limits. During the summer of 2023, we recorded substrate temperatures exceeding 63°C at our study site in Half Moon Bay, marking the highest temperatures ever documented (Kaminski et al., 2023). Similarly, in the ostracod experiment, specimens exposed to water coverage or their natural habitat exhibited greater adaptability and tolerance to high temperatures in the Bahrain area compared to our tested gastropods.

2.7 Conclusions

Based on our experimental investigations involving intertidal-lagoonal biocalcifying organisms from the Arabian Gulf, we have reached several significant conclusions. Our tested specimens exhibit remarkably high upper thermal limits when subjected to various scenarios. In the case of the gastropod specimen, almost all scenarios revealed a Heat Comma Temperature (HCT) close to or exceeding 40°C for both substrate and water temperatures. Notably, the scenario involving complete water immersion showed even higher HCT and CT100 values, reaching up to 48°C. In contrast, the ostracod specimen displayed even greater resilience during the heat experiments, with HCT values close to 40°C and upper lethal temperatures surpassing 45°C. The CT100 reached as high as 48°C, and the LT100 peaked at 53.5°C. Another notable outcome from our experiments is that both the gastropod and ostracod specimens exhibited a distinctive trait characterized by temporary immobility during and after heat exposure, followed by a gradual return to normal activity. The duration of this immobile state increased as the level of heat stress intensified. This finding provides valuable insights into the resilience of biocalcifiers that inhabit the extreme environment of the Arabian Gulf, characterized by rapid temperature

fluctuations, particularly during the peak of the summer season, and addresses the potential impacts of future global warming.

CHAPTER 3

OCCURRENCE OF MORPHOLOGICAL DEFORMITIES

WITHIN BENTHIC FORAMINIFERA DUE TO

POSSIBLE ENVIRONMENTAL PARAMETERS IN THE

WESTERN ARABIAN GULF AREA

Submitted in Journal of Foraminiferal Research

3.1 Abstract

This study investigates the naturally stressed environment of the western Arabian Gulf, where extreme levels of salinity exist compared to the eastern side. We aim to understand how hypersaline conditions affect the living benthic foraminiferal communities, particularly those insensitive to natural variability. We recorded the variability of foraminifera communities, including their diversity and abundances, across different salinity levels at selected localities, and examined the occurrence of morphological deformities within the collected materials. The Rose Bengal-stained materials were used to determine the proportions of living and dead specimens and quantify morphological deformities. In the stained samples, we recorded a total of 109 species of benthic foraminifera, mostly of the Order Miliolida. The stained samples revealed that approximately one-quarter of foraminifera specimens were living at the time of sampling.

We observed various forms of morphological deformities with different degrees of severity and an increasing percentage of deformities across a salinity gradient above 40 PSU or hypersalinity in both sample types (averaging above 40%). Environmental analysis of marine sediment samples revealed no dangerous levels of anthropogenic stressors, such as trace elements and organic constituents (very low to below detection limit). Therefore, most probably the occurrence of morphological deformities within foraminifera tests may be a result of either salinity-induced constraints or changes in salinity during their lifetime across different seasons, as they are primarily observed in the adult forms or more developed specimens.

Keywords: morphological deformities, benthic foraminifera, hypersaline, Arabian Gulf

3.2 Introduction

Assessing the influence of environmental stressors on ecosystem communities in scientific research requires a critical initial step, namely the selection of target organisms (Holt and Miller, 2010). This becomes especially pertinent in light of the escalating threat of climate change to marine environments, necessitating a meticulous choice of marine communities from a multidisciplinary perspective (Kaiho, 2022; Pinsky et al., 2022). Foraminifera prove to be invaluable tools for environmental monitoring due to their capacity to produce shells that endure in the fossil record and their rapid adaptability to diverse stressors (Sabbatini et al., 2014; Martins et al., 2019).

Originally employed as index fossils for sedimentary rock dating (Grzybowski, 1898; Cushman, 1948), contemporary foraminiferal assemblages offer versatility, providing not only insights into recent environmental conditions (Sen Gupta, 1999a; Murray, 2006) but also serving as proxies for paleotemperature, paleoproductivity, oxygen levels, and

fluctuations in sea levels (Kaiho, 1994; Valchev, 2003; Groeneveld and Filipsson, 2013; Kaminski et al., 2018; Lane et al., 2023;). Furthermore, they hold the potential for forecasting, enabling the prediction of their spatial distribution in response to environmental alterations (Merkado et al., 2013; Weinmann et al., 2013; Kenigsberg et al., 2022;), as well as their capacity to withstand the extreme conditions projected for future decades (Titelboim et al., 2016, 2019; Pinko et al., 2020).

Benthic foraminifera exhibit a wide range of strategies to respond to intraspecific stressors, showing adaptability to both natural and anthropogenic challenges through modifications in community-level structure and composition (Murray, 2006; Jones, 2013). These responses encompass alterations in diversity patterns (Hess et al., 2001), the proliferation of opportunistic species (Hart et al., 2022), gradual adjustments in the face of mass mortality events (Hess et al., 2001; Hikmahtiar et al., 2022), and the occurrences of varying degrees of abnormalities in their tests (Yanko et al., 1994; 1998; Geslin et al., 2000). Particularly regarding the occurrence of test structure alterations in foraminifera, understanding the primary factors and controls behind these changes represents a significant challenge. Even in relatively natural or undisturbed environments, these organisms may exhibit morphological deformities (Yanko et al., 1994, 1998; Stouff et al., 1999). Furthermore, in exceptionally extreme hypersaline conditions, the frequency and diversity of morphological deformities in foraminifera are notably higher (Clarke and Keij, 1973; Amao et al., 2018; Fiorini and Lokier, 2020).

Numerous investigations have explored the influence of environmental disturbances on living organisms, with a particular focus on foraminifera. These studies have employed controlled experiments using cultured specimens exposed to natural and anthropogenic

stressors. While a range of experiments have been carried out, the primary stressors imposed on foraminifera typically involve pollutants such as trace elements and organic substances (Saraswat et al., 2004; Barras et al., 2018; Price et al., 2019). Furthermore, certain inquiries have delved into the impact of natural stressors, specifically conditions induced by variations in salinity, on the deformation of foraminiferal test morphology. For instance, Stouff et al. (1999) observed that hyaline-test specimens of *Ammonia tepida* born under high salinity conditions exhibited morphological deformities in later stages at a rate of 50%, in contrast to only 1% in individuals born under normal conditions. Similarly, when salinity is reduced to levels lower than those found in normal seawater (hyposaline conditions), Charrieau et al. (2018) identified decalcification and aberrant test structures in select species of *Ammonia* and *Elphidium crispum*. These findings offer valuable insights into how environmental stressors can affect the morphology of foraminifera, showcasing their sensitivity and capacity to respond to alterations in their environment.

In the Arabian Gulf, a broad spectrum of environmental conditions, encompassing both undisturbed natural areas and heavily polluted regions, coexist, exerting significant influences on benthic communities, with particular focus on foraminifera (Price and Sheppard, 1991; Price et al., 1993; Sheppard et al., 1992, 2010). Despite the Gulf's division into five zones based on benthic foraminifera communities by Amao et al. (2022), there has been a notable gap in the research concerning foraminiferal populations and their adaptations to the extreme conditions of the western side, characterized by high temperatures and salinity. Climate projections for the future indicate a further temperature increase, and the proliferation of desalinization plants along the coastline will lead to even more hypersaline conditions by the mid-21st century (Pal and Eltahir, 2016; Safieddine et

al., 2022), particularly in intertidal, shallow waters, and lagoon areas. As such, this study sought to investigate the diversity of foraminifera and the potential emergence of morphological abnormalities in response to varying salinity levels at different locations within ostensibly natural (unpolluted) environments.

3.3 Study Site

Initially, we designated eight distinct locations to represent a spectrum of hypersaline conditions. These potential sites encompassed six intertidal and lagoonal areas in Saudi Arabia, along with two intertidal areas in Bahrain. The selection criteria were founded on their pristine status, far removed from anthropogenic activities, a characterization supported by previous research (Arslan et al., 2016a, 2017). To facilitate meaningful comparisons, we included another pristine site in Saudi Arabia that exhibited nearly identical conditions but lacked prior foraminifera-focused investigations. Our team collected sediment samples concurrently during the early winter period of December 2022, spanning from the second to the fourth week. The choice of sampling locations was also guided by additional insights from the study conducted by Amao et al. (2022), which underscored the importance of further exploration in these regions. In the end, we selected six of these locales as our primary sampling targets for analysis in this study (see Figure 14).

3.4 Materials and Methods

3.4.1 Material Samplings

We obtained surface sediments, situated approximately 0.5 to 1 cm beneath the bottom-set surface, directly from our study site using glass sample jars measuring 5 cm in diameter and 10 cm in height. These samples represented recently accumulated materials. Each jar

was filled with a mixture consisting of 30% sediments and 70% water. We collected two different types of samples, each serving distinct purposes. Stained samples were obtained from each location to evaluate the diversity of living benthic foraminifera. These samples were stained with Rose Bengal in a 70% ethanol solution, following the guidelines recommended by the FOBIMO group for foraminiferal monitoring (Schönfeld et al., 2012). In addition to the stained and unstained samples, we collected fresh untreated samples and water samples for grain size, trace element, and organic carbon analyses. Subsequently, these samples were transported to the Micropaleontology Laboratory at King Fahd University of Petroleum & Minerals for further analysis and investigation.

3.4.2 Field and Laboratory Physio-chemical Analysis

To evaluate the ecological condition of our sampling sites, we carried out both field and laboratory assessments of the physical and chemical attributes of water and sediment. In the field, we employed a multiparameter probe (Hanna HI98194) to measure pH, salinity (in PSU and/or mS/cm), and temperature (in °C) at the time of sampling.

For our freshly collected sediment samples, we conducted analyses for trace elements and organic constituents to gauge the natural conditions. We initiated the process by drying 0.25 grams of the sediment sample at 30°C for 24 hours, followed by digestion in 10 ml of nitric acid and subsequent dilution to 100 ml according to EPA 3050 Method. We focused on trace element parameters, including manganese (Mn), chromium (Cr), copper (Cu), nickel (Ni), arsenic (As), lead (Pb), cadmium (Cd), zinc (Zn), and mercury (Hg), utilizing the iCAP RQ ICP-MS (Inductively Coupled Plasma Mass Spectrometry).

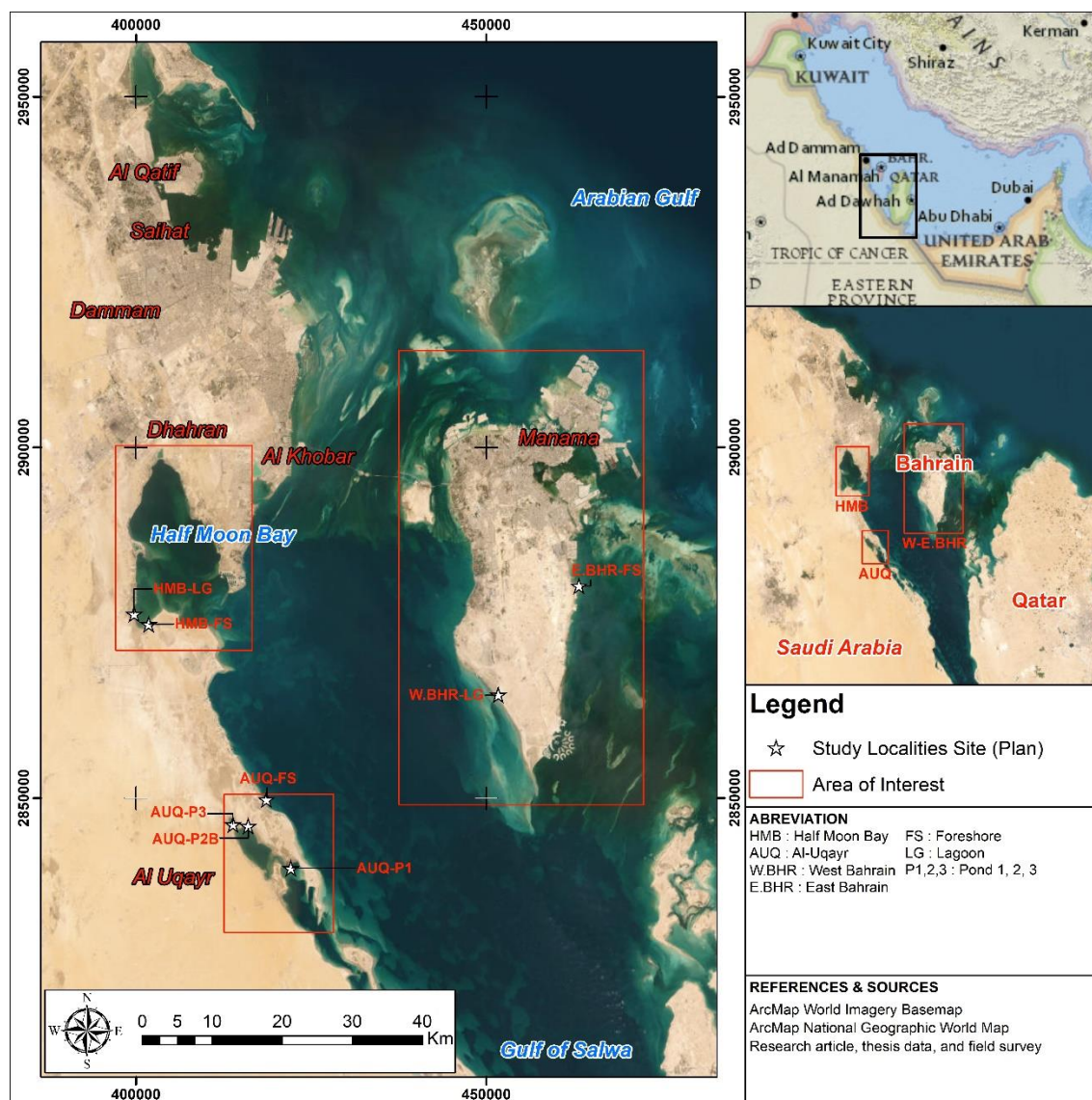


Figure 14. Map of the sediment and foraminiferal sampling locality in this study.

Within the same laboratory, we quantified the organic constituents in our samples, specifically total organic carbon (TOC) and total carbon (TC) content. To do this, we employed the Elementar Soli TOC Cube TOC ANALYZER and adhered to modified versions of DIN19539 protocols for the analysis. About 25 mg of dried sediments were analyzed in porcelain cups, with two replicates for each sample to account for possible errors. As a quality control measure, we also analyzed similar amounts of calcium carbonate (CaCO_3) and glucose to establish baseline values. The organic carbon

constituents were derived by exposing the materials to elevated temperatures with a 200°C difference.

Additionally, we conducted a grain size distribution analysis using the HELOS Particle Size Analysis. One mg of unwashed wet material was introduced into the apparatus, yielding various datasets such as cumulative distribution and distribution density as representative characteristics of our samples.

3.4.3 Foraminifera Sample Preparation, Sampling and Identification

Within this study we only consider using the protein-staining material for the entire works. For the usage of stained samples, a waiting period of at least two weeks was imposed to allow for the proper reaction of the staining agent with the specimens. We followed similar washing and preparation procedures, but extended the duration to ensure thorough removal of the Rose Bengal stain. Likewise, around 300 specimens were chosen from subsamples after the aliquot division, but in this case, all benthic foraminifera (comprising larger benthic foraminifera/LBF and smaller benthic foraminifera/SBF) were selected from the materials.

Taxonomic identification was performed for the stained and picked foraminiferal materials. Our references included the monograph by Loeblich and Tappan (1987), along with previously published materials from adjacent regions (Murray, 1970; Cherif et al., 1997; Arslan et al., 2016a; Amao et al., 2016, 2018) for identification purposes. We categorized the specimens as dominant, normal, or deformed test specimens, distinguishing between living and dead assemblages within the stained materials, while also considering the ratio of life-dead assemblages and the possible lethality induced by deformities. For detailed

species identification, representative specimens were selected for scanning electron microscopy imaging using the GEOL 7000 Desktop SEM. The materials used in this study are currently archived in the Micropaleontology Laboratory of KFUPM for educational purposes.

3.4.4 Data Visualization

We conducted a range of statistical analyses to assess the foraminiferal assemblages. These analyses included computing diversity indices such as relative abundance for each taxon, species richness (S), dominance (D), the Shannon-Wiener index (H'), evenness (e^H/S), and Fisher's alpha. These calculations were performed using PAST v4.03 software (Hammer and Harper, 2001). To compare the characteristics of living and deceased specimens, as well as the deformed and undeformed test specimens within our dataset, we utilized Excel and Python to organize the data and create informative graphs that effectively convey our findings.

3.5 Results

3.5.1 Environmental Quality Assessment of Sampled Localities

The field data collected from six different locations reveals a degree of hypersaline conditions and generally normal pH levels. In open marine areas like EBH-FS, the salinity levels surpass the typical seawater values (40 PSU) but remain lower than other locations, not exceeding 50 PSU, such as in HMB-FS at 60.1 PSU and AUQ-P3 at 68.5 PSU. The pH levels in the sampling area consistently register above 8, falling within the range of 8.2 to 8.5. The temperature data reflects relatively cooler conditions typical of winter, with temperatures ranging from 22 to 25°C across the sampling sites.

Table 1 provides a summary of the laboratory analysis of sediment samples from each location, complementing the field data. The results for trace elements reveal very low or undetectable levels, or in certain cases, concentrations below the detection limit (BDL). These values for the listed elements do not exceed the international standards. For example, the limit for lead (Pb) in marine sediments is 40 PPM, while all our samples measure less than 2 PPM. Only two samples exhibited slightly higher levels for nickel (Ni) and arsenic (As), but this was not the case for all trace elements. The analysis of organic constituents (TOC and TC) also indicates that the levels are below hazardous or limit thresholds, with values ranging from 0.16% to 1.79% for TOC and 1.02% to 10.4% for TC. Furthermore, the grain size analysis reveals a consistent trend, with materials primarily falling within the 3 Φ to 1 Φ range, representing sand-sized particles comprising 95% to 99% of the total composition (X50 to X99).

Table 1. Physical and chemical components/parameters within our sediment sample based on laboratory analysis

Parameters	Unit	HMB-FS	EBH-FS	AUQ-FS	AUQ-P1	AUQ-P2	AUQ-P3
Temperature (seawater)	°C	22.50	22.10	21.70	20.80	20.50	20.10
Salinity (seawater)	PSU	60.01	44.50	53.50	58.44	64.48	67.11
pH (seawater)	-	8.12	8.32	8.28	8.26	8.25	8.23
TOC (sediments)	%	1.79	0.91	1.64	0.36	0.16	0.23
TC (sediments)	%	10.36	1.82	8.36	2.85	1.19	1.02
Mn (sediments)	ppm	30.61	26.77	44.96	35.72	47.02	41.82
Cr (sediments)	ppm	9.99	18.33	16.34	12.00	23.05	16.15
Cu (sediments)	ppm	1.82	3.12	2.55	2.24	2.65	2.29
Ni (sediments)	ppm	18.09	14.42	21.97	17.14	25.24	17.71
As (sediments)	ppm	3.64	1.02	3.50	2.27	1.47	1.25
Pb (sediments)	ppm	1.07	1.42	1.32	1.54	1.42	1.08
Cd (sediments)	ppm	1.89	0.61	BDL	BDL	BDL	BDL
Zn (sediments)	ppm	16.84	11.45	13.50	12.66	15.68	7.64
Hg (sediments)	ppm	0.70	1.00	0.13	0.37	3.19	0.18

3.5.2 Benthic Foraminiferal Diversity

Among the six stained samples, which included both LBF and SBF specimens, we identified three orders of foraminifera: Miliolida, Rotaliida, and Textulariida. We

discerned around 30 or more species at each locality based on morphological characteristics, although some species were classified only at the genus level due to identification challenges. Notably, the EBH-FS locality exhibited the highest species diversity, with a total of 74 species, while AUQ-P2 displayed the lowest, with 32 species. Considering the use of 50-gram sediment in our analysis, EBH-FS had the highest number of specimens per gram of sediment, with 3,092 specimens per gram, while AUQ-P2 had the lowest at 32 specimens per gram. Our examination of diversity indices revealed that AUQ-P1 displayed the highest dominance (D), EBH-FS registered the highest Shannon Index (H'), HMB-FS exhibited the highest evenness ($e^{H/S}$), and EBH-FS yielded the highest Fisher Alpha Index. Comprehensive statistical results regarding diversity indices are provided in Table 2 and Plate 1-3. The list of benthic foraminifera presented below comprises only those with relative abundances exceeding 2.5% for at least one locality. For the complete list, please refer to the Supplementary materials or Appendix 1.

3.5.3 Live-Dead Comparison and Normal-Deformed Morphology Occurrences

Analyzing the rose Bengal stained samples, we found that the living fauna in each locality accounted for over 25% of the total specimens selected. When considering the genera present, they were ranked in descending order of living abundances as follows: Peneroplis, Triloculina, Ammonia, Miliolinella, Quinqueloculina, Elphidium, Monalysidium, and Coscinospira. A visual depiction of these comparisons between living and deceased assemblages is given in Figure 15.

In our analysis of the sampled materials, we observed that LBF exhibited a higher occurrence of morphological deformities, exceeding 40%, in comparison to SBF across all

salinity gradients. This trend remained consistent regardless of their higher taxonomic order categorization (rotaliids and miliolids), as illustrated in Figure 16. Among LBF specimens, Peneroplis had the highest percentage of deformities, followed by Coscinospira and Monalysidium, as shown in Plate 4 and 5.

Table 2. List of statistical parameter and species of foraminifera founded in this study

Parameter/Species	Sampling Stations					
	HMB-FS	EBH-FS	AUQ-FS	AUQ-P1	AUQ-P2	AUQ-P3
Taxa_S	58	74	59	37	32	35
Individuals	263	303	266	211	200	217
Dominance_D	0.04	0.10	0.05	0.13	0.09	0.06
Shannon_H'	3.49	3.21	3.34	2.63	2.79	3.07
Evenness_e^H/S	0.57	0.33	0.48	0.38	0.51	0.62
Fisher_alpha	23.02	31.21	23.49	13.00	10.76	11.81
Total_Bulk_Per_Grams	674	3,092	170	270	32	69
<i>Coscinospira hemprichii</i> (Ehrenberg, 1839)	0.00	7.92	1.13	4.74	0.00	0.00
<i>Monalysidium aciculare</i> (Batsch, 1791)	7.60	10.23	3.76	10.43	0.00	0.00
<i>Peneroplis pertusus</i> (Forsskål in Niebuhr, 1775)	9.89	27.39	4.89	31.28	23.00	4.15
<i>Miliolinella chukchiensis</i> (Loeblich & Tappan, 1953)	0.00	1.65	5.64	0.47	0.00	0.00
<i>Miliolinella fichteliana</i> (d'Orbigny, 1839)	5.70	2.31	11.65	3.79	12.00	14.29
<i>Pseudotriloculina hottingeri</i> (Amao & Kaminski, 2017)	2.28	3.30	7.52	7.58	12.50	14.75
<i>Pseudotriloculina</i> sp.	0.00	0.00	0.75	0.47	4.00	0.00
<i>Quinqueloculina akneriana</i> (d'Orbigny, 1846)	5.32	1.32	0.00	4.27	0.00	2.30
<i>Quinqueloculina carinatastriata</i> (Wiesner, 1923)	1.90	0.66	1.13	6.64	5.00	1.84
<i>Quinqueloculina</i> sp. 17 (Amao, 2016)	3.42	0.33	0.00	0.00	1.00	1.84
<i>Quinqueloculina</i> sp. 22 (Amao, 2016)	0.76	0.00	0.00	0.00	2.50	0.00
<i>Quinqueloculina</i> sp. 32 (Amao, 2016)	0.00	0.66	0.00	0.00	1.00	4.61
<i>Quinqueloculina</i> sp. 33 (Amao, 2016)	0.00	0.66	0.00	0.00	5.00	3.23
<i>Sigmoilina canisementis</i> (Kaminski, Garisson & Waskowska, 2020)	7.60	0.99	0.00	0.00	0.00	0.00
<i>Triloculina schreiberiana</i> (d'Orbigny, 1839)	1.52	0.66	9.02	0.47	0.00	0.00
<i>Triloculina</i> sp. 05 (Amao, 2016)	0.76	0.33	7.52	1.42	1.00	4.61
<i>Triloculina</i> sp.	3.04	0.66	0.38	0.00	0.00	0.00
<i>Triloculina</i> sp. 04	0.00	0.00	0.75	3.32	0.00	0.00
<i>Triloculina</i> sp. 08	2.66	0.66	1.13	4.74	2.00	1.38
<i>Triloculina vespertilio</i> (Zheng, 1988)	3.04	1.65	5.26	0.95	1.50	0.92
<i>Ammonia abramovitchae</i> (Hayward & Holzmann, 2021)	0.76	1.65	2.26	0.00	2.00	4.15
<i>Ammonia arabica</i> (Kaushik, 2021)	4.18	0.66	1.50	0.00	0.00	2.76
<i>Ammonia</i> sp. (Amao, 2016)	1.14	0.33	1.88	1.90	3.00	0.00
<i>Ammonia</i> sp. 03	0.00	0.66	0.38	0.47	0.00	3.23
<i>Ammonia tepida</i> (Cushman, 1926)	0.00	0.66	3.38	0.00	1.50	0.00
<i>Ammonia veneta</i> (Schultze, 1854)	0.38	0.99	0.38	0.00	0.00	4.61
<i>Elphidium hispidulum</i> (Cushman, 1936)	0.76	0.00	3.01	0.00	0.00	0.00
<i>Elphidium macellum</i> (Fichtel & Moll, 1798)	0.00	1.32	0.38	0.95	2.50	2.76
<i>Elphidium tongaense</i> (Cushman, 1931)	0.76	1.98	0.00	0.95	2.50	4.15
<i>Glabratellina</i> sp.	3.80	0.33	0.00	0.00	0.00	0.00

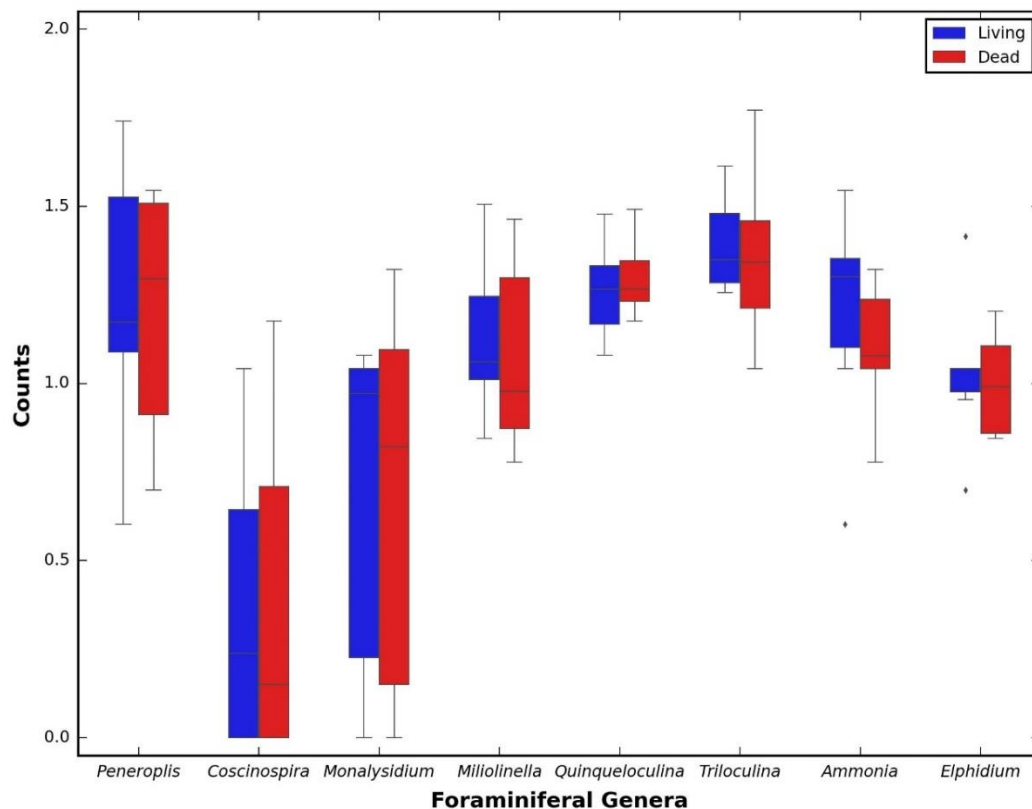


Figure 15. Boxplot representing comparison of living and dead assemblages from our sampling area. The raw value is converted with log transformation $[\log(1 + x)]$ to shows the trends.

For SBF, *Ammonia* displayed the most morphological deformities, followed by *Elphidium*. These two genera accounted for anywhere from 25% to over 75% of the total assemblages at the genus level. In contrast, the Miliolidea superfamily (*Quinqueloculina*, *Triloculina*, *Spiroloculina*, *Agglutinella*, *Pseudotriloculina*, and *Miliolinella*) exhibited a smaller proportion of morphological deformities, amounting to less than 30% (typically around 25% to 30%) of the total individuals in their respective genera under lower hypersaline conditions. This percentage gradually increased to above 50% at higher salinities exceeding 60 PSU, as showed in Plate 6 and 7.

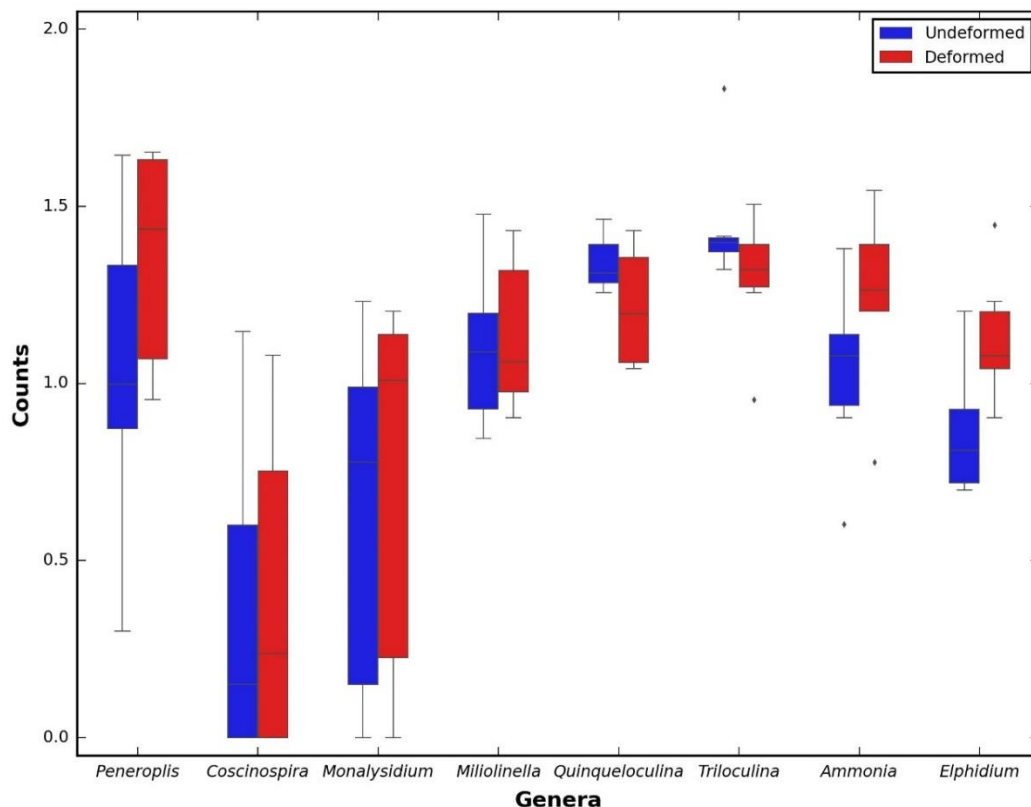


Figure 16. Boxplot representing comparison of undeformed and deformed assemblages from our sampling area. The raw value is converted with log transformation $[\log(1 + x)]$ to shows the trends.

The observed deformities expressed a spectrum of variations, ranging from mild, such as highly trochospiral, multiple chamber sizes, size reduction, and apertural modifications, to more severe deformations, including twinning, constriction, coiling plane modifications, and bifurcation. Notably, around 50% of the deformed specimens were identified in the adult forms, particularly in LBF that had reached later stages, like flaring in *Peneroplis* and uncoiled forms in *Coscinospira* and *Monalysidium*. In contrast, fewer than 10% of the deformities were observed in juvenile stages. Similar patterns were also observed in SBF specimens, such as *Ammonia*, *Elphidium*, and Loculinid. In these cases, deformities were predominantly found in the final chamber, or they did not occur or were rarely observed in

the early stages of their development. The incidence of deformities was particularly high, exceeding 75% among the deformed specimens.

3.6 Discussions

The western Arabian Gulf, particularly the eastern regions of Saudi Arabia and Bahrain, experiences significant temperature and salinity fluctuations, especially during the summer months (Amao et al., 2022; Kaminski et al., 2021a, 2023). Even during our winter sampling period, we recorded temperatures below 25°C, and one locality exhibited hypersaline conditions with salinity values reaching as high as 67 PSU. Moreover, data from in-situ temperature monitoring conducted by Kaminski et al. (2023) indicated warm water temperatures exceeding 35°C, with field measurements showing substrate temperatures exceeding 50°C. Organisms in this region, including foraminifera, may respond to these extreme conditions in various ways, such as by tolerating high temperatures (Prazeres et al., 2015; Schmidt et al., 2016), increasing reproductive efforts to adapt to the challenges (Schönfeld and Numberger, 2007; Amao et al., 2018), or potentially entering periods of partial hibernation or dormancy (Ross and Hallock, 2016).

The primary objective of this study is to investigate the previously documented instances of morphological deformities within benthic foraminiferal communities in the western Arabian Gulf (Amao et al., 2018). The previous report suggested that salinity might be the predominant factor leading to these deformities, as the influence of other anthropogenic factors, such as trace elements and petroleum hydrocarbons, appeared limited. However, the sampling sites they examined had nearly identical salinity levels. In contrast, our study encompasses several closely situated locations with varying salinity levels. Our goal is to identify the common causes of morphological deformities in foraminifera, with a particular

focus on the potential impact of anthropogenic pollution. Nevertheless, we acknowledge that natural factors, including changes in salinity and hydrodynamic effects, may also contribute to deformities, albeit to a lesser degree (Yanko et al., 1994, 1998, 1999; Geslin et al., 2000, 2002; Frontalini and Coccioni, 2011).

Furthermore, it is essential to recognize that morphological deformities are not a recent or modern phenomenon. Fossil records of foraminifera have shown deformities in the absence of human or anthropogenic influence (Antonarakou et al., 2018; Coccioni and Luciani, 2006; Ferrandez-Canadell et al., 2014). This historical context underscores the importance of investigating how morphological deformities can arise in natural or naturally stressed environments, making it a compelling area of research.

3.6.1 Environmental Data Interpretation

The sampling locations within the western Arabian Gulf, which encompass Half Moon Bay and Al-Uqayr in Saudi Arabia, as well as the East Bahrain Foreshore, are situated in intertidal to shallow water environments, characterized by an average depth not exceeding 10 meters Amao et al. (2022). These sites are classified as pristine areas with minimal human influence, a designation in line with Murray's criteria (2006). It is worth noting that this region is naturally stressed, given the elevated levels of salinity and temperatures, especially during the summer season. Additionally, certain areas, as identified by Kaminski et al. (2021a, 20223), have been recognized as potential "kill zones," particularly within intertidal zones and ephemeral lagoons.

The sediment composition at our sampling sites primarily comprises sand-sized particles, representing the predominant fraction (ranging from 95 to 99%). This composition implies that the sediment is predominantly sourced from nearby origins, such as sand dunes or

aeolian deposits. As previously noted by Amao et al. (2018), the localities in the western Arabian Gulf typically feature sand-sized materials, with hardened substrates formed from lithified bioclastic materials due to seasonal exposure to elevated temperatures and oversaturated saline water, as documented by Weijermars (1999b).

Furthermore, the sediment composition also contains fragments of other calcifying invertebrates, including mollusks (both bivalves and gastropods) and ostracod carapaces. This discovery aligns with the findings of (Kaminski et al., 2021a) in Bahrain, where abundant meiofaunal communities were observed in the intertidal zone. This suggests that these communities might either be transported into the mudflats during the tidal flooding cycle or be conveyed by migratory carrier organisms like birds. There is also the possibility of transport by vessels into the Arabian Gulf, as noted by Sheppard et al. (2010) and Vaughan et al. (2018). Additionally, in some instances, benthic foraminifera may be unintentionally transported by mud adhering to the feet of migratory birds, as mentioned by Sen Gupta (1999b) and (Holzmann and Pawlowski, 2017).

Upon analyzing trace elements and organic constituents, our findings revealed that all samples contained very low to undetectable levels of contaminants. These results align with the conclusions drawn by Amao et al. (2018) and Arslan et al. (2016a, 2017), which suggest minimal human influence in the studied areas. An additional factor contributing to the low detection of anthropogenic substances may be the prevalence of sandy sediment. It is noteworthy that most of the mentioned anthropogenic constituents tend to be preserved or adsorbed within finer materials, such as mud, as described by Rao et al. (2008) and Martins et al. (2011).

3.6.2 Benthic Foraminifera Assemblages, Deformity, and Possible Origin

For the general assemblages, encompassing both SBF and LBF, miliolids dominate the composition, reflecting their ecological preferences in the Arabian Gulf (Murray, 2006; Amao et al., 2022). Notably, we did not observe any significant relationship between the relative abundances of benthic foraminifera and the presence of organic and inorganic pollutants from the nearby sampling sites in the western Arabian Gulf, consistent with previous findings (Arslan et al., 2016a, 2017). It is important to highlight that the abundance of LBF is notably higher in more open marine areas within samples labeled with the "foreshore" (FS) code, with a higher prevalence in the middle and Pond 3s of the Al-Uqayr lagoonal system, specifically AUQ-P2 and P3.

Morphological deformities predominantly manifest in the adult life stages of Large Benthic Foraminifera (LBF), particularly in the uncoiled sections of *Coscinospira* and *Monalysidium*, as well as the flared portions of *Peneroplis*, in contrast to the juvenile planispiral parts. This observation is in line with previous studies by Clarke and Keij (1973) and Fiorini and Lokier (2020), which suggest that these aberrant test features primarily appear in adults or more advanced life stages, implying that external stressors likely trigger these morphological abnormalities later in life.

Furthermore, our examination of stained specimens revealed the presence of deformed individuals, suggesting that these deformities are not lethal. Similar example has been observed in environments affected by high levels of pollution due to human activities, where foraminifera exhibited aberrant tests but managed to survive (Yanko et al., 1994, 1998, 1999; Geslin et al., 2002; Pati and Patra, 2012; Amao et al., 2018). Experimental studies involving cultured specimens induced by trace elements have also shown that

morphological deformities do not necessarily result in lethality (Stouff et al., 1999; de Nooijer et al., 2007; Nigam et al., 2009; Saraswat et al., 2015; Price et al., 2019). Considering our findings, which indicate low levels of anthropogenic stressors, the most plausible explanation for these abnormalities is associated with the heightened hypersaline conditions observed in confined water bodies within the Gulf.

Salinity is widely acknowledged as a pivotal factor influencing the calcification process and the incorporation of elements, such as magnesium and calcium, in the construction of foraminiferal tests (Dissard et al., 2010; Charrieau et al., 2018; Geerken et al., 2018). Another potential factor contributing to the development of aberrant tests, albeit closely intertwined with salinity, is the seasonal variation in salinity levels. During the peak or typical summer period, the western Arabian Gulf often experiences salinity levels exceeding 60 PSU, which then decrease in the winter to approximately 50 to 55 PSU, representing a variation of 5 to 10 PSU, especially in enclosed lagoons (Joydas et al., 2015, 2023; Nazeer et al., 2021).

Benthic foraminifera exhibit a preference for stable or normal conditions when it comes to reproduction, thriving in conditions marked by suitable temperatures and salinity. In less favorable conditions, they may maintain their adult form while continuing to grow, as evidenced in fossil records during periods of environmental stress characterized by atypical temperatures, such as during the late Paleocene and early to mid-Eocene, or the Late Paleocene Thermal Maximum (BouDagher-Fadel, 2008; Speijer et al., 2012; Schmidt et al., 2018; Hallock and Seddighi, 2022). The observation that deformed tests are primarily found in the adult life stages and rarely in the juvenile or undeveloped stages suggests that these specimens underwent reproduction during environmentally favorable conditions,

with subsequent salinity fluctuations leading to abnormalities in their growth. However, these assumptions require further validation through experimental works involving culture-based specimens in controlled laboratory setup to test this hypothesis.

3.7 Conclusions

In this research, we conducted extensive observation of benthic foraminifera assemblages in several locations across the western Arabian Gulf, chosen for their representation of pristine yet naturally stressed environments. Simultaneously, we quantified the occurrences of morphological deformities among the foraminifera. Our selected sampling sites encompassed a spectrum of salinity levels exceeding the regional norm (above 40 PSU) and exhibited minimal to negligible human interference, evident through the low presence of pollutants. Species diversity at these sites was relatively limited, with an average species richness of around 49 and diversity indices averaging at 3.09. Both living and dead foraminiferal assemblages were predominantly characterized by larger benthic foraminiferal genera, namely *Peneroplis*, *Coscinospira*, and *Monalysidium*, and smaller benthic foraminiferal genera *Quinqueloculina* and *Triloculina* in open foreshore and less constrained areas. In contrast, calcareous genera like *Ammonia*, *Elphidium*, and smaller miliolids were more prevalent in confined environments. Morphological abnormalities were frequently observed in the LBF assemblages, reaching levels exceeding 40%, and were rarely found in juvenile specimens. The SBF displayed a lower occurrence of such abnormalities, and the deformities observed were less complex. The low levels of anthropogenic pollutants, including trace elements and organic content, did not exhibit any suspicious causal relationship with foraminiferal test deformities. This leads us to the conclusion that deformities manifest naturally in unpolluted locality, primarily under the

influence of abnormally high salinity, whether due to salinity levels difference or seasonal variations. Further comprehensive sampling throughout the study area and future experimental studies involving cultured specimens will be essential to validate and expand upon these findings.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions based on This Study

Based on this study, we can conclude from our findings into followings statement:

1. Based on the Chapter 2, the living intertidal biocalcifiers from the Western Arabian Gulf locality exhibit higher thermal tolerance in particular (due to no comparison from other biota from the adjacent area), where the experimental specimen can sustain high temperature above 40°C, even 50°C before eventually died in the processes;
2. Based on the Chapter 3, the naturally stressed environment of Arabian Gulf, especially in the western portion have high diversity of benthic foraminifera, where a quarter of sampled materials were living during sampling and multiple morphological deformities were also observed, despite of relatively pristine condition in regards of anthropogenic inducer except the salinity aspect;
3. Statistical analysis based on the diversity indices shows that in the area that have more connection to the open ocean (Arabian Gulf) have more diversity and total bulk per gram, compared to more restricted area.

4.2 Future Recommendations/Suggestions based on This Study

Considering from our major concern about the background of this study, while also addressing the conclusion from this study and some explained limitation based on each

chapter, several future recommendation or suggestion are being provided in the following sections:

1. Conducting more thermal experimental approach towards various intertidal and shallow water communities in the Arabian Gulf, to testify the general assumption from this study where in particular, the animals that inhabit the region are having high thermal resilience;
2. Using more controlled instrumentation during the thermal experiment, such as using thermal bath instead of incubator, for more precise and standardized procedure in the future similar works, as well as redo the current experiment with the abovementioned instrument to calibrate the current findings;
3. Prolonged the exposure time with more varied in timing and temperature, and maintain direct observation, to clarify in which period did the specimen exhibit such behavior (comatose/immobilize);
4. Additional sampling across the Western Arabian Gulf while maintaining the sufficient number and spacing between each location to generate more representative result, as well as proper material for statistical analysis.

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APPENDICES

Appendix 1: List of foraminiferal genus and species found, along with their relative abundance (%) from each locality within this study

SPECIES	HMB-FS	EBH-FS	AUQ-FS	AUQ-P1	AUQ-P2	AUQ-P3
<i>Coscinospira hemprichii</i> (Ehrenberg, 1839)	0.00	7.92	1.12	4.78	0.00	0.00
<i>Monahysidium aciculare</i> (Batsch, 1791)	7.60	10.23	3.75	10.53	0.00	0.00
<i>Peneroplis arietinus</i> (Batsch, 1791)	0.00	0.33	0.37	0.96	0.00	0.00
<i>Peneroplis pertusus</i> (Forsskål in Niebuhr, 1775)	9.89	27.39	4.87	31.58	23.00	4.15
<i>Peneroplis planatus</i> (Fichtel & Moll, 1798)	0.76	0.66	0.37	0.96	0.00	0.00
<i>Sortes orbiculus</i> (Forsskål in Niebuhr, 1775)	0.00	0.33	0.00	0.00	0.00	0.00
<i>Vertebrulina striata</i> (d'Orbigny, 1826)	0.00	0.33	0.00	0.00	0.00	0.00
<i>Agglutinella kaminskii</i> (Garrison, 2019)	0.38	0.99	0.00	0.48	0.00	0.46
<i>Agglutinella robusta</i> (El-Nakhal, 1983)	1.14	0.99	0.00	0.00	0.00	0.46
<i>Agglutinella soriformis</i> (El-Nakhal, 1983)	0.38	0.66	0.00	0.00	0.00	0.00
<i>Flintina</i> sp. (Amao, 2016)	0.00	0.33	0.37	0.48	0.00	0.00
<i>Cycloforina quinquecarinata</i> (Collins, 1958)	0.00	0.00	0.75	0.00	0.00	0.00
<i>Miliolinella chukchiensis</i> (Loeblich & Tappan, 1953)	0.00	1.65	5.62	0.48	0.00	0.00
<i>Miliolinella circularis</i> (Bornemann, 1855)	0.00	0.66	1.12	0.00	0.00	2.30
<i>Miliolinella fichteliana</i> (d'Orbigny, 1839)	5.70	2.31	11.61	3.83	12.00	14.29
<i>Miliolinella hybrida</i> (Terquem, 1878)	0.76	0.66	0.75	2.39	2.00	0.92
<i>Milonella</i> sp.	0.00	0.33	0.37	0.00	0.00	0.00
<i>Milonella</i> sp. 1	0.38	0.66	0.00	0.00	0.50	0.00
<i>Milonella</i> sp. 2	0.38	0.66	0.00	0.00	0.50	0.00
<i>Milonella</i> sp. 3	0.00	0.00	0.37	0.00	0.00	0.00
<i>Milonella</i> sp. 1 (Amao, 2016)	0.38	1.32	0.37	0.00	0.00	0.00
<i>Miliolinella valvularis</i> (Reuss, 1851)	0.00	0.00	0.37	0.00	0.00	0.00
<i>Pseudolachlanella eburnea</i> (d'Orbigny, 1839)	0.00	0.66	0.37	0.48	0.00	0.00
<i>Pseudotriloculina hottingeri</i> (Amao & Kaminski, 2017)	2.28	3.30	7.49	7.66	12.50	14.75
<i>Pseudotriloculina subgranulata</i> (Cushman, 1918)	0.76	0.66	0.00	0.48	0.00	0.00
<i>Pseudotriloculina</i> sp.	0.00	0.00	0.75	0.48	4.00	0.00
<i>Pseudotriloculina</i> sp. 1	0.76	0.33	0.00	0.00	0.00	0.00
<i>Pseudotriloculina</i> sp. 2	1.14	0.00	0.00	0.00	0.00	0.00
<i>Pseudotriloculina</i> sp. 3	0.00	0.00	0.75	0.00	0.00	0.00
<i>Quinqueloculina agglutinans</i> (d'Orbigny, 1839)	0.00	0.00	0.00	0.00	0.00	0.00
<i>Quinqueloculina akneriana</i> (d'Orbigny, 1846)	5.32	1.32	0.00	4.31	0.00	2.30
<i>Quinqueloculina bidentata</i> (d'Orbigny, 1839)	0.00	0.66	0.00	0.00	0.00	0.00
<i>Quinqueloculina bubnanensis</i> (McCulloch, 1977)	0.38	0.00	0.37	0.96	0.50	0.00
<i>Quinqueloculina carinatastriata</i> (Wiesner, 1923)	1.90	0.66	1.12	6.70	5.00	1.84
<i>Quinqueloculina myagmarsuren</i> (Parker, 2009)	0.76	0.66	0.00	0.00	0.00	1.38
<i>Quinqueloculina poeyana</i> (d'Orbigny, 1839)	0.76	0.00	1.87	0.00	0.00	0.00
<i>Quinqueloculina seminulum</i> (Linnaeus, 1758)	0.76	0.66	1.50	0.00	0.00	0.00
<i>Quinqueloculina</i> sp.	0.76	0.66	0.00	0.00	0.00	1.84
<i>Quinqueloculina</i> sp. 1	0.00	0.33	0.00	0.00	0.00	0.00
<i>Quinqueloculina</i> sp. 2	0.38	0.66	0.00	0.00	0.00	0.00
<i>Quinqueloculina</i> sp. 3	0.00	0.00	0.00	0.48	0.00	0.00
<i>Quinqueloculina</i> sp. 4	0.00	0.00	0.37	0.00	0.00	0.00
<i>Quinqueloculina</i> sp. 5	0.00	0.00	0.75	0.00	0.00	0.00
<i>Quinqueloculina</i> sp. 6	0.00	0.00	0.37	0.00	0.00	0.00
<i>Quinqueloculina</i> sp. 7	0.00	0.00	0.37	0.00	0.00	0.00
<i>Quinqueloculina</i> sp. 8	0.00	0.00	0.37	0.00	0.00	0.00
<i>Quinqueloculina</i> sp. 9	0.00	0.00	0.75	0.00	0.00	0.00
<i>Quinqueloculina</i> sp. 10	0.00	0.66	1.12	0.00	0.00	0.00
<i>Quinqueloculina</i> sp. 11	0.00	0.00	0.00	0.00	1.00	0.00
<i>Quinqueloculina</i> sp. (Amao, 2016)	0.00	0.66	0.00	0.00	0.00	0.00
<i>Quinqueloculina</i> sp. 09 (Amao, 2016)	1.14	0.33	0.37	0.00	0.00	0.00
<i>Quinqueloculina</i> sp. 17 (Amao, 2016)	3.42	0.33	0.00	0.00	1.00	1.84
<i>Quinqueloculina</i> sp. 18 (Amao, 2016)	0.76	0.33	0.00	0.00	0.00	0.00
<i>Quinqueloculina</i> sp. 19 (Amao, 2016)	0.38	0.99	0.00	0.00	0.00	2.30
<i>Quinqueloculina</i> sp. 22 (Amao, 2016)	0.76	0.00	0.00	0.00	2.50	0.00
<i>Quinqueloculina</i> sp. 24 (Amao, 2016)	1.14	0.66	0.00	0.96	1.50	0.92
<i>Quinqueloculina</i> sp. 27 (Amao, 2016)	0.76	0.33	0.75	0.96	1.00	0.00
<i>Quinqueloculina</i> sp. 32 (Amao, 2016)	0.00	0.66	0.00	0.00	1.00	4.61
<i>Quinqueloculina</i> sp. 33 (Amao, 2016)	0.00	0.66	0.00	0.00	5.00	3.23
<i>Quinqueloculina</i> sp. 34 (Amao, 2016)	0.00	0.33	0.00	0.00	0.00	0.92
<i>Sigmulina canisements</i> (Kaminski, Garisson & Waskowska, 2020)	7.60	0.99	0.00	0.00	0.00	0.00
<i>Triloculina schreiberiana</i> (d'Orbigny, 1839)	1.52	0.66	8.99	0.48	0.00	0.00
<i>Triloculina</i> sp. 05 (Amao, 2016)	0.76	0.33	7.49	1.44	1.00	4.61
<i>Triloculina</i> sp.	3.04	0.66	0.37	0.00	0.00	0.00
<i>Triloculina</i> sp. 01	0.00	0.33	0.00	0.00	0.00	0.00
<i>Triloculina</i> sp. 02	0.00	0.33	0.00	0.00	0.00	0.00
<i>Triloculina</i> sp. 03	0.00	0.00	0.75	0.00	0.00	0.00
<i>Triloculina</i> sp. 04	0.00	0.00	0.75	3.35	0.00	0.00
<i>Triloculina</i> sp. 05	0.00	0.33	1.12	0.00	0.00	0.00
<i>Triloculina</i> sp. 06	0.00	0.00	1.50	0.00	0.00	0.00
<i>Triloculina</i> sp. 07	1.14	0.00	0.75	0.00	1.00	0.00
<i>Triloculina</i> sp. 08	2.66	0.66	1.12	3.83	2.00	1.38
<i>Triloculina vespertilio</i> (Zheng, 1988)	3.04	1.65	5.24	0.96	1.50	0.92
<i>Spiroloculina</i> sp.	0.38	0.00	0.00	0.00	0.00	0.00
<i>Spiroloculina</i> sp. 1	0.00	0.33	0.00	0.00	0.00	0.00
<i>Spiroloculina</i> sp. 2	0.00	0.33	0.37	0.00	0.00	0.00
<i>Rosalina</i> sp.	0.38	0.33	0.00	0.00	0.00	0.00
<i>Rosalina</i> sp. 1	0.00	0.00	0.37	0.00	0.00	0.00
<i>Glabratellina</i> sp.	3.80	0.33	0.00	0.00	0.00	0.00
<i>Glabratellina</i> sp. 1	1.90	0.00	0.00	0.48	0.00	0.00
<i>Glabratellina</i> sp. 2	1.14	0.00	0.00	0.48	0.00	0.00
<i>Elphidium advena</i> (Cushman, 1922)	0.38	0.66	0.00	0.00	1.00	2.30
<i>Elphidium excavatum</i> (Terquem, 1875)	1.14	0.66	0.00	0.96	0.00	0.00
<i>Elphidium fichtelianum</i> (d'Orbigny, 1846)	0.00	1.65	0.00	0.00	0.00	0.00
<i>Elphidium gerthi</i> (van Voorthuysen, 1957)	0.38	0.00	0.37	0.00	0.00	0.00
<i>Elphidium hawkesburyense</i> (Albani, 1974)	0.00	0.00	0.00	0.00	0.00	0.46
<i>Elphidium hispidulum</i> (Cushman, 1936)	0.76	0.00	3.00	0.00	0.00	0.00
<i>Elphidium indicum</i> (Cushman, 1936)	0.00	0.00	0.00	0.96	0.00	1.84
<i>Elphidium macellum</i> (Fichtel & Moll, 1798)	0.00	1.32	0.37	0.96	2.50	2.76
<i>Elphidium maorium</i> (Hayward, 1997)	0.76	1.98	1.87	0.00	1.50	0.00

<i>Elphidium tongaense</i> (Cushman, 1931)	0.76	1.98	0.00	0.96	2.50	4.15
<i>Elphidium</i> sp.	0.00	0.00	0.75	0.96	2.00	0.46
<i>Elphidium</i> sp. 1	1.90	0.00	1.12	0.48	1.00	0.46
<i>Elphidium</i> sp. 2	0.00	0.00	0.00	0.00	0.00	1.84
<i>Ammonia aberdoveyensis</i> (Haynes, 1973)	2.28	1.65	0.37	0.00	2.00	0.00
<i>Ammonia abramovichae</i> (Hayward & Holzmann, 2021)	0.76	1.65	2.25	0.00	2.00	4.15
<i>Ammonia arabica</i> (Kaushik, 2021)	4.18	0.66	1.50	0.00	0.00	2.76
<i>Ammonia beccarii</i> (Linnaeus, 1758)	0.00	0.66	1.50	0.48	0.00	2.30
<i>Ammonia goldsteiniae</i> (Hayward & Holzmann, 2021)	1.14	0.00	0.00	0.00	1.00	1.84
<i>Ammonia</i> sp. (Amao, 2016)	1.14	0.33	1.87	1.91	3.00	0.00
<i>Ammonia</i> sp. 01 (Amao, 2016)	0.00	0.33	0.00	0.96	0.00	0.00
<i>Ammonia</i> sp. 02 (Amao, 2016)	0.76	0.33	0.00	0.00	1.50	0.00
<i>Ammonia</i> sp.	2.28	0.00	0.37	0.00	0.00	0.00
<i>Ammonia</i> sp. 01	1.52	0.33	0.00	0.00	0.00	1.38
<i>Ammonia</i> sp. 02	0.00	0.99	0.00	0.00	0.00	0.00
<i>Ammonia</i> sp. 03	0.00	0.66	0.37	0.48	0.00	3.23
<i>Ammonia tepida</i> (Cushman, 1926)	0.00	0.66	3.37	0.00	1.50	0.00
<i>Ammonia veneta</i> (Schultze, 1854)	0.38	0.99	0.37	0.00	0.00	4.61
<i>Clavulina angularis</i>	0.00	0.33	0.00	0.00	0.00	0.00
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00

Plate 1

All scale bars are 100 μ m. otherwise mentioned on the scale bar

1 a-c *Monalysidium aciculare* (Batsch, 1791), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, juvenile/planispiral form.

2 a-c *Monalysidium aciculare* (Batsch, 1791), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, adult/planispiral with slightly uncoiled form.

3 a-c *Monalysidium aciculare* (Batsch, 1791), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, adult/planispiral and uncoiled form.

4 a-c *Peneroplis planatus* (Fichtel & Moll, 1798), (a) apertural, (b) lateral, and (c) other lateral side view, Half Moon bay locality, juvenile/planispiral form.

5 a-c *Peneroplis planatus* (Fichtel & Moll, 1798), (a) apertural, (b) lateral, and (c) other lateral side view, Half Moon bay locality, adult/planispiral and later become flaring form.

6 a-c *Peneroplis planatus* (Fichtel & Moll, 1798), (a) apertural, (b) lateral, and (c) other lateral side view, Half Moon bay locality, adult/ planispiral and later become flaring form.

7 a-c *Peneroplis pertusus* (Forsskål in Niebuhr, 1775), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality, juvenile/planispiral form.

8 a-c *Peneroplis pertusus* (Forsskål in Niebuhr, 1775), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality, adult/planispiral and later become slightly uncoiled form.

9 a-c *Peneroplis pertusus* (Forsskål in Niebuhr, 1775), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality, adult/ planispiral and later become uncoiled form.

10 a-c *Coscinospira hemprichii* (Ehrenberg, 1839), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality, juvenile/planispiral form.

11 a-c *Coscinospira hemprichii* (Ehrenberg, 1839), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality, adult/planispiral and later become slightly uncoiled form.

12 a-c *Coscinospira hemprichii* (Ehrenberg, 1839), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality, adult/ planispiral and later become uncoiled form.

13 a-b *Sorites orbiculus* (Forsskål in Niebuhr, 1775), (a) lateral view (b) other lateral side view, East Bahrain locality, adult/ planispiral and later become uncoiled form.

Plate 1

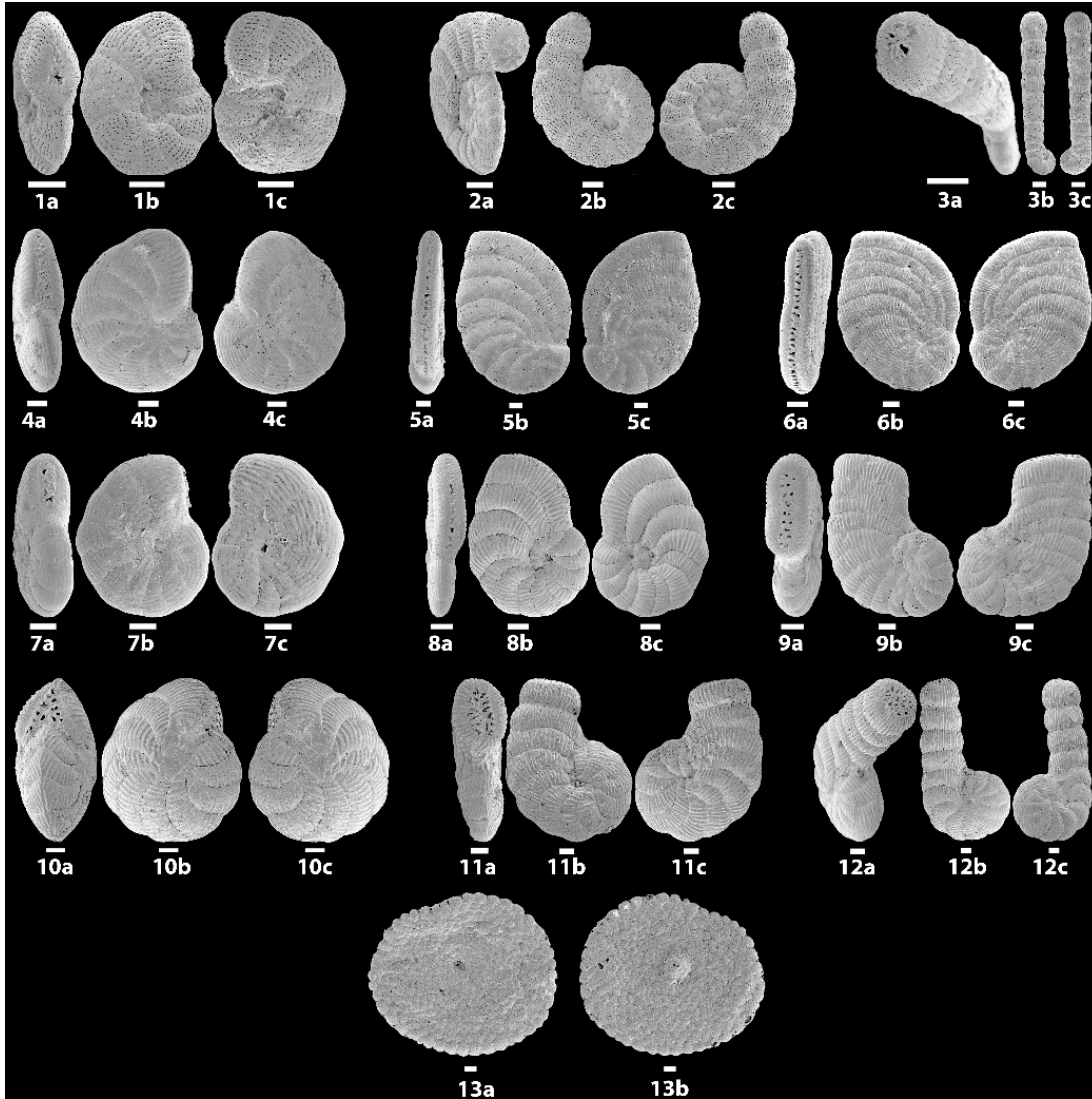


Plate 2

All scale bars are 100 μ m. otherwise mentioned on the scale bar

- 1 a-c *Ammonia abramovichae* (Hayward & Holzmann, 2021 in Hayward et al., 2021), (a) side view, (b) spiral view, and (c) umbilical view, East Bahrain locality.
- 2 a-c *Ammonia beccarii* (Linnaeus, 1758), (a) side view, (b) spiral view, and (c) umbilical view, East Bahrain locality.
- 3 a-c *Ammonia* sp., (a) side view, (b) spiral view, and (c) umbilical view, Uqair Foreshore locality.
- 4 a-c *Ammonia* sp. (Amao, 2016), (a) side view, (b) spiral view, and (c) umbilical view, Uqair Foreshore locality.
- 5 a-c *Ammonia aberdoyensis* (Haynes, 1973), (a) side view, (b) spiral view, and (c) umbilical view, East Bahrain locality.
- 6 a-c *Ammonia goldsteiniae* (Hayward & Holzmann, 2021 in Hayward et al., 2021), (a) side view, (b) spiral view, and (c) umbilical view, East Bahrain locality.
- 7 a-c *Ammonia* sp.01. (a) side view, (b) spiral view, and (c) umbilical view, Uqair Foreshore locality.
- 8 a-c *Elphidium excavatum* (Terquem, 1875), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
- 9 a-c *Elphidium hispidulum* (Cushman, 1936), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Pond 1 locality.
- 10 a-c *Elphidium advena* (Cushman, 1922), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Pond 1 locality.

- 11 a-c *Elphidium macellum* (Fichtel & Moll, 1798), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.
- 12 a-c *Elphidium gerthi* (van Voorthuysen, 1957), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.
- 13 a-c *Elphidium indicum* (Cushman, 1936), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.
- 14 a-c *Elphidium tongaense* (Cushman, 1931), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.
- 15 a-c *Elphidium maorium* (Hayward, 1997), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.
- 16 a-c *Elphidium* sp. (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
- 17 a-c *Rosalina* sp. (a) side view, (b) spiral view, and (c) umbilical view, East Bahrain locality.
- 18 a-c *Glabratellina* sp. (a) side view, (b) spiral view, and (c) umbilical view, Half Moon bay locality.
- 19 a-c *Glabratellina* sp.1. (a) side view, (b) spiral view, and (c) umbilical view, Half Moon bay locality.
- 20 a-c *Clavulina angularis* (d'Orbigny, 1826), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.
- 21 a-c *Vertebralina striata* (d'Orbigny, 1826), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.

Plate 2

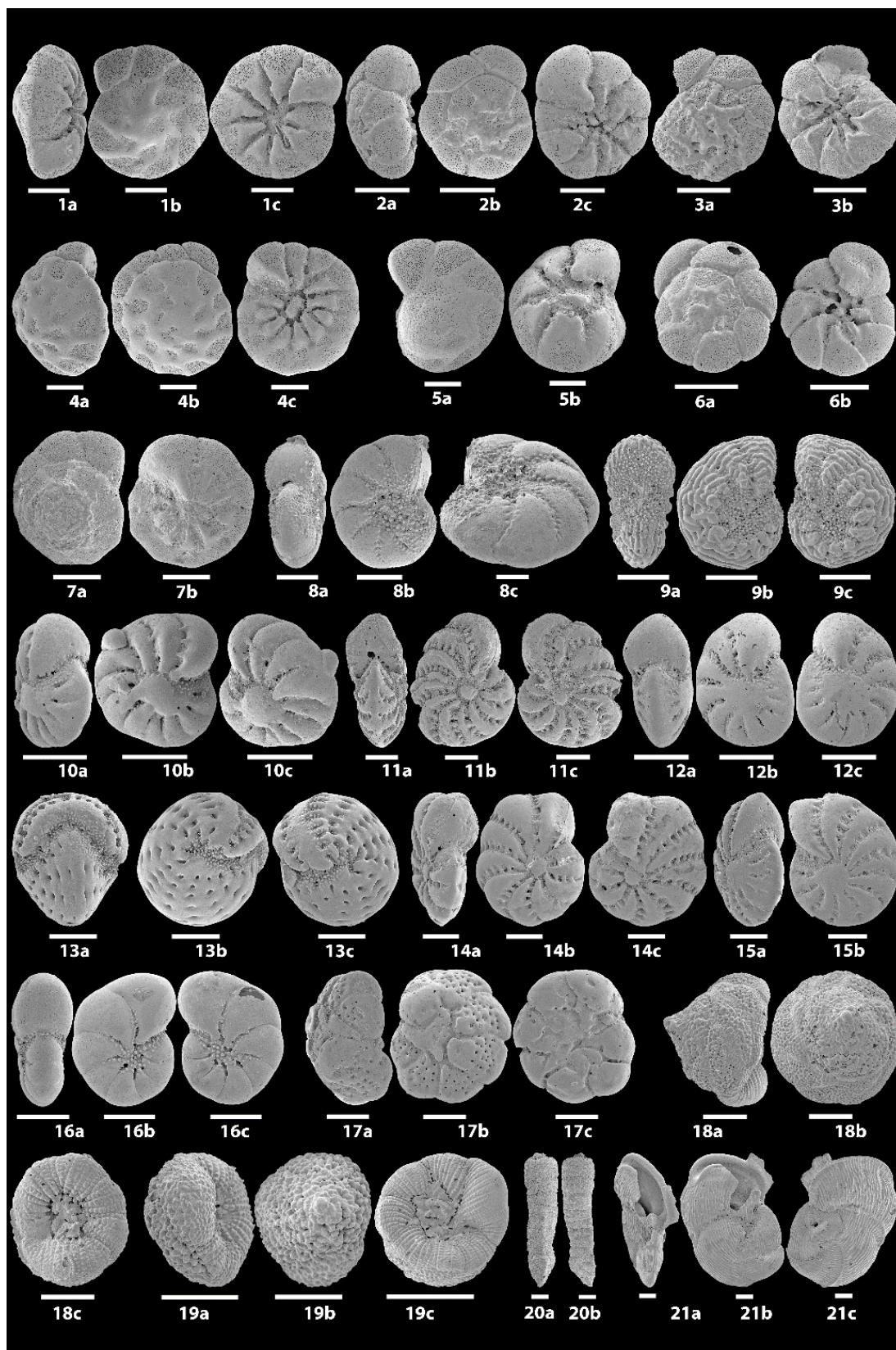


Plate 3

All scale bars are 100 µm. otherwise mentioned on the scale bar

1 a-c *Agglutinella kaminskii* (Garrison, 2019), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.
 2 a-c *Agglutinella soriformis* (Garrison, 2019), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.
 3-4 a-c *Pseudotriloculina hottingeri* (Garrison, 2019), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.
 5 a-c *Miliolinella chukchiensis* (Loeblich & Tappan, 1953), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
 6 a-c *Miliolinella hybrida* (Terquem, 1878), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.
 7 a-c *Miliolinella* sp. (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
 8 a-c *Quinqueloculina carinatastriata* (Wiesner, 1923), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.
 9 a-c *Quinqueloculina* sp.18. (Amao, 2016), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
 10 a-c *Quinqueloculina* sp.27. (Amao, 2016), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
 11 a-c *Quinqueloculina poeyana* (d'Orbigny, 1839), (a) apertural, (b) lateral, and (c) other lateral side view, Half Moon bay locality.
 12 a-c *Quinqueloculina bubnaensis* (McCulloch, 1977), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
 13 a-c *Quinqueloculina* sp.33. (Amao, 2016), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.

14 a-c *Quinqueloculina* sp. (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
 15 a-c *Quinqueloculina* sp.01. (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
 16 a-c *Quinqueloculina* sp.02. (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
 17 a-c *Quinqueloculina akneriana* (d'Orbigny, 1846), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality.
 18 a-c *Sigmoilina canisdementis* (Kaminski, Garisson & Waskowska, 2020), (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality locality.
 19 a-c *Spiroloculina* sp. (a) apertural, (b) lateral, and (c) other lateral side view, East Bahrain locality locality.
 20 a-c *Miliolinella fichteliana* (d'Orbigny, 1839), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
 21 a-c *Triloculina vespertilio* (Zheng, 1988)), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
 22 a-c *Triloculina* sp., (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Pond 1 locality.
 23 a-c *Triloculina* sp.01., (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.
 24 a-c *Triloculina* sp.05. (Amao, 2016), (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality.

Plate 3

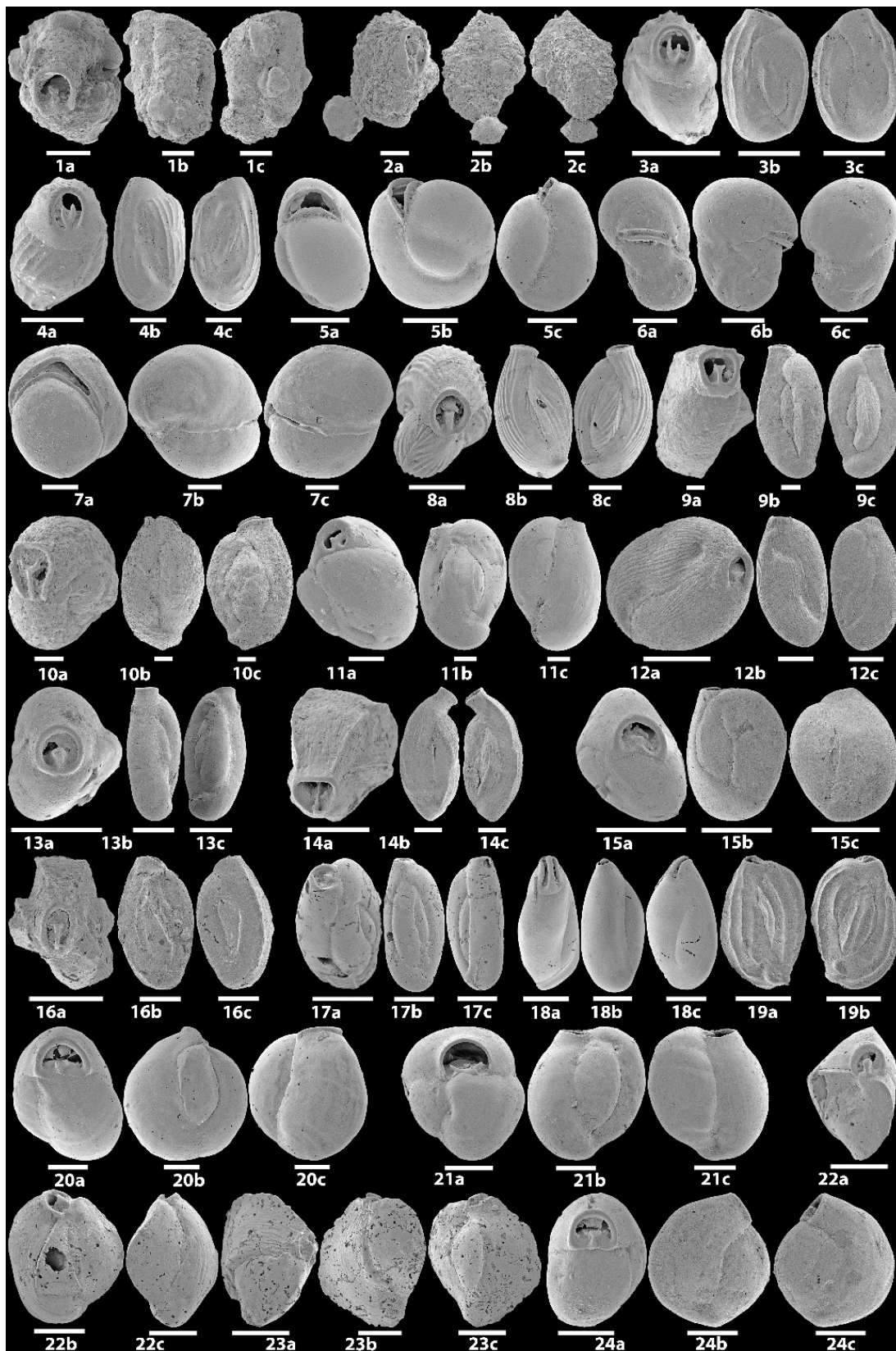


Plate 4

All scale bars are 100 μ m. otherwise mentioned on the scale bar

- 1 a-c *Monalysidium aciculare*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, chamber shrinkage.
- 2 a-c *Monalysidium aciculare*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, chamber expansion.
- 3 a-c *Monalysidium aciculare*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, overdevelopment.
- 4 a-c *Monalysidium aciculare*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, dented chamber.
- 5 a-c *Monalysidium aciculare*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, wrong coiling orientation.
- 6 a-c *Monalysidium aciculare*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, strange aperture and change in coiling plane.
- 7 a-c *Monalysidium aciculare*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, multiple final chamber development/overdevelopment.
- 8 a-b *Monalysidium aciculare*, (a) apertural view (b) lateral view, Uqair Foreshore locality, deformed, overdevelopment and weird aperture development.
- 9 a-b *Monalysidium aciculare*, (a) apertural view (b) lateral view, Uqair Foreshore locality, deformed, branching twins.
- 10 a-c *Peneroplis planatus*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, wrong coiling orientation.

- 11 a-c *Peneroplis planatus*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, chamber shrinkage and dented.
- 12 a-c *Peneroplis planatus*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, overdevelopment.
- 13 a-c *Peneroplis planatus*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, septum separating the aperture.
- 14 a-c *Peneroplis planatus*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, certain chamber shrinkage.
- 15 a-c *Peneroplis planatus*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, multiple final chamber growth with similar form/twinning.
- 16 a-c *Peneroplis planatus*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, overdevelopment and dented chamber.
- 17 a-c *Peneroplis planatus*, (a) apertural view (b) lateral view, Uqair Foreshore locality, deformed, apertural strange development and change in coiling plane.
- 18 a-c *Peneroplis planatus*, (a) apertural view (b) lateral view, Uqair Foreshore locality, deformed, strange apertural opening and final chamber development.
- 19-21 a-c *Peneroplis planatus*, (a) apertural view (b) lateral view, and (c) other lateral side view, Uqair Foreshore locality, deformed, multiple final chamber development with different form/bifurcation.

Plate 4

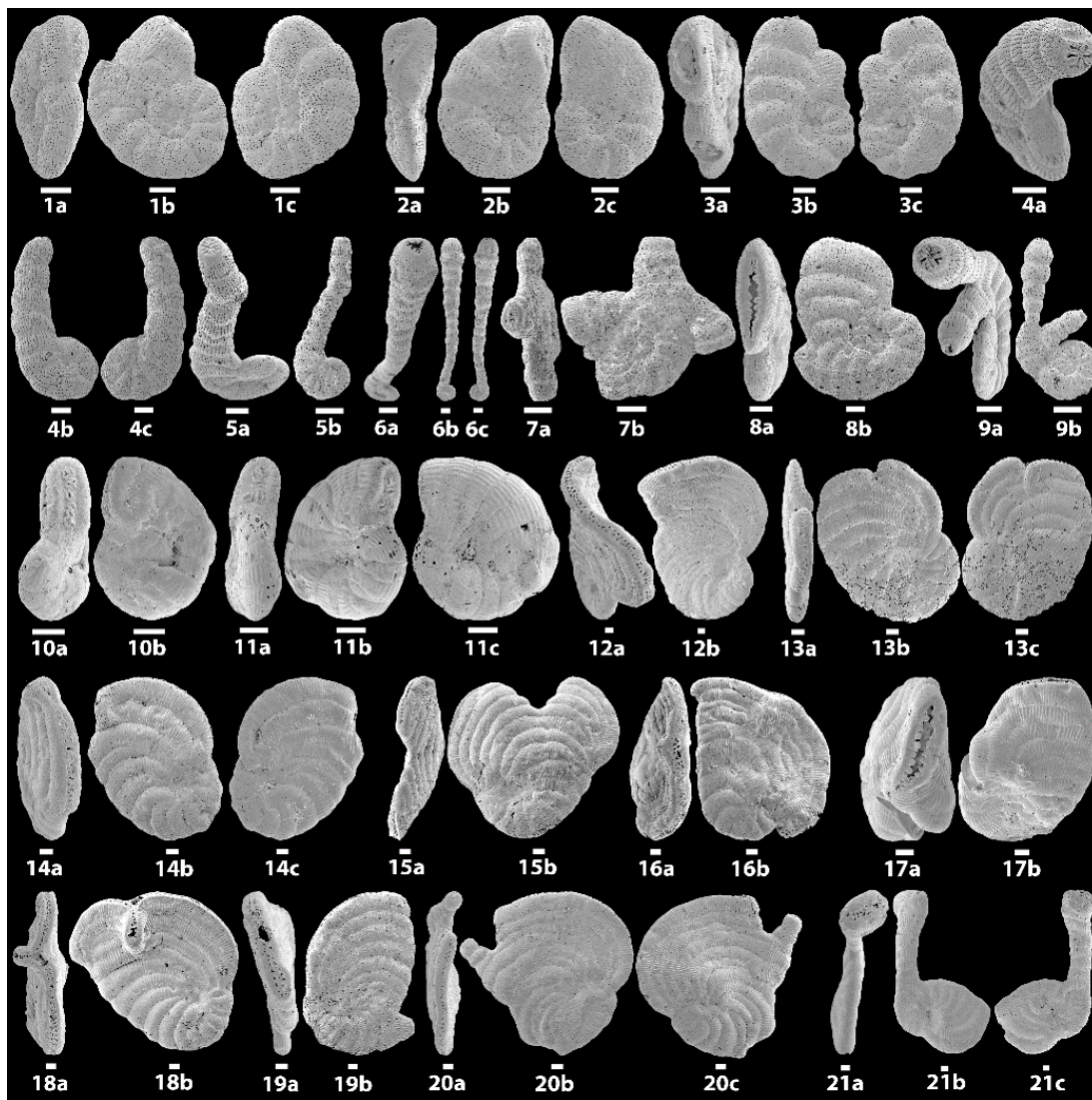


Plate 5

All scale bars are 100 μ m. otherwise mentioned on the scale bar

1 a-b *Peneroplis pertusus*, (a) apertural view (b) lateral view, Uqair Foreshore locality, deformed, multiple chamber development with similar shape/twinning.

2 a-c *Peneroplis pertusus*, (a) apertural view (b) lateral view, Uqair Foreshore locality, deformed, wrong coiling plane development.

3 a-b *Peneroplis pertusus*, (a) apertural view (b) lateral view, Uqair Foreshore locality, deformed, septum separating the final chamber and aperture.

4 a-b *Peneroplis pertusus*, (a) apertural view (b) lateral view, Uqair Foreshore locality, deformed, multiple development from different side.

5 a-b *Peneroplis pertusus*, (a) apertural view (b) lateral view, Uqair Foreshore locality, deformed, multiple development of similar form in one body/twinning.

6 a-c *Coscinospira hemprichii*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, wrong coiling development.

7 a-c *Coscinospira hemprichii*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, multiple growth of different form/bifurcation.

8 a-c *Coscinospira hemprichii*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair

Foreshore locality, deformed, dented and shrinkage of certain chamber.

9 a-c *Coscinospira hemprichii*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, offset chamber development.

10-11 a-c *Coscinospira hemprichii*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, wrong coiling orientation development.

12 a-c *Coscinospira hemprichii*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, weird apertural development.

13 a-c *Coscinospira hemprichii*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, multiple form development from different type/bifurcation.

14 a-c *Coscinospira hemprichii*, (a) apertural, (b) lateral, and (c) other lateral side view, Uqair Foreshore locality, deformed, coiling plane change.

15 a-b *Sorites orbiculus*, (a) lateral view (b) lateral view of the opposite side, Uqair Foreshore locality, deformed, overdevelopment and change in coiling orientation.

Plate 5

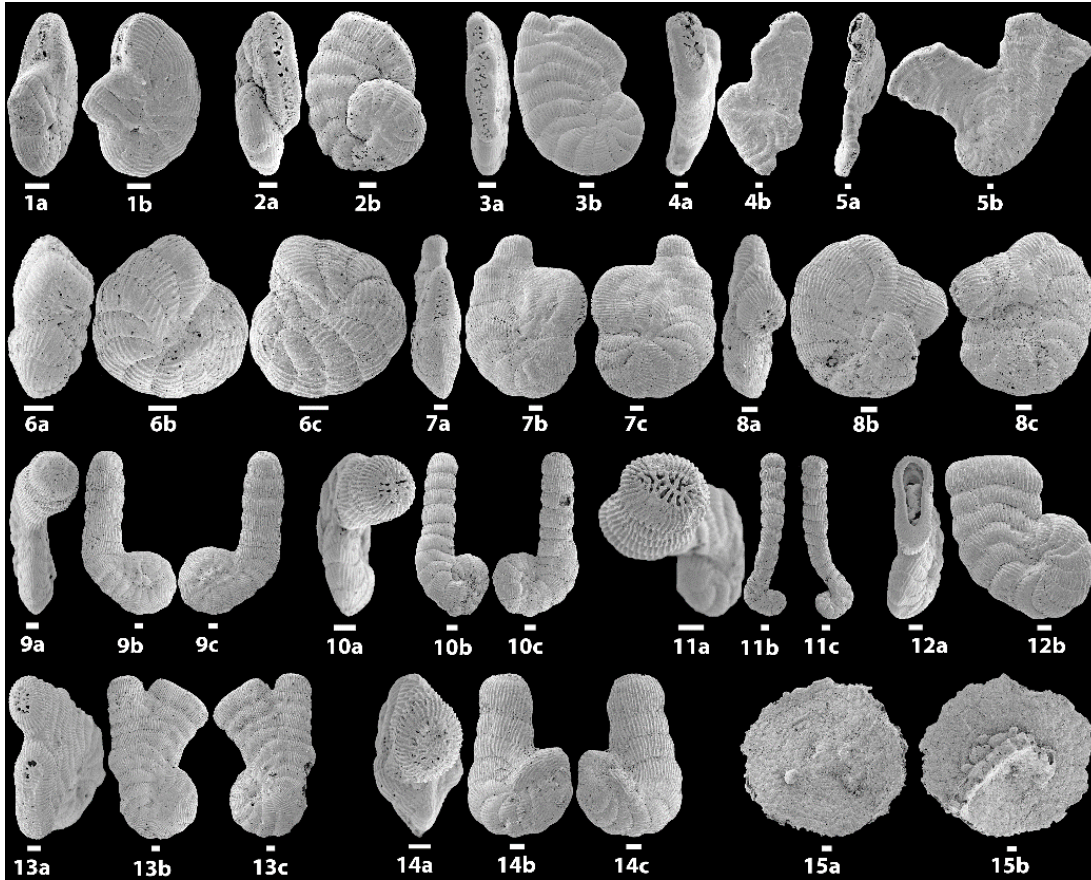


Plate 6

All scale bars are 100 μ m. otherwise mentioned on the scale bar

1 a-c *Ammonia* sp., (a) side view, (b) spiral view, and (c) umbilical view, deformed, overgrowing and overdevelopment in the final chamber.

2 a-c *Ammonia* sp., (a) side view, (b) spiral view, and (c) umbilical view, deformed, become elongated and dented chamber.

3 a-c *Ammonia* sp., (a) side view, (b) spiral view, and (c) umbilical view, deformed, become highly trochospiral.

4 a-c *Ammonia* sp., (a) side view, (b) spiral view, and (c) umbilical view, deformed, become highly trochospiral and bizarre development in the spiral side.

5 a-c *Ammonia* sp., (a) side view, (b) spiral view, and (c) umbilical view, deformed, flatten spiral side.

6 a-c *Elphidium* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, occurrences of protuberance.

7 a-c *Elphidium* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, dented and undeveloped chamber.

8 a-c *Elphidium* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, sunken last chamber and dented.

9 a-c *Elphidium* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, overdevelopment of certain chamber.

10 a-c *Elphidium* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, obliterated apertural face and dented chamber.

Plate 6

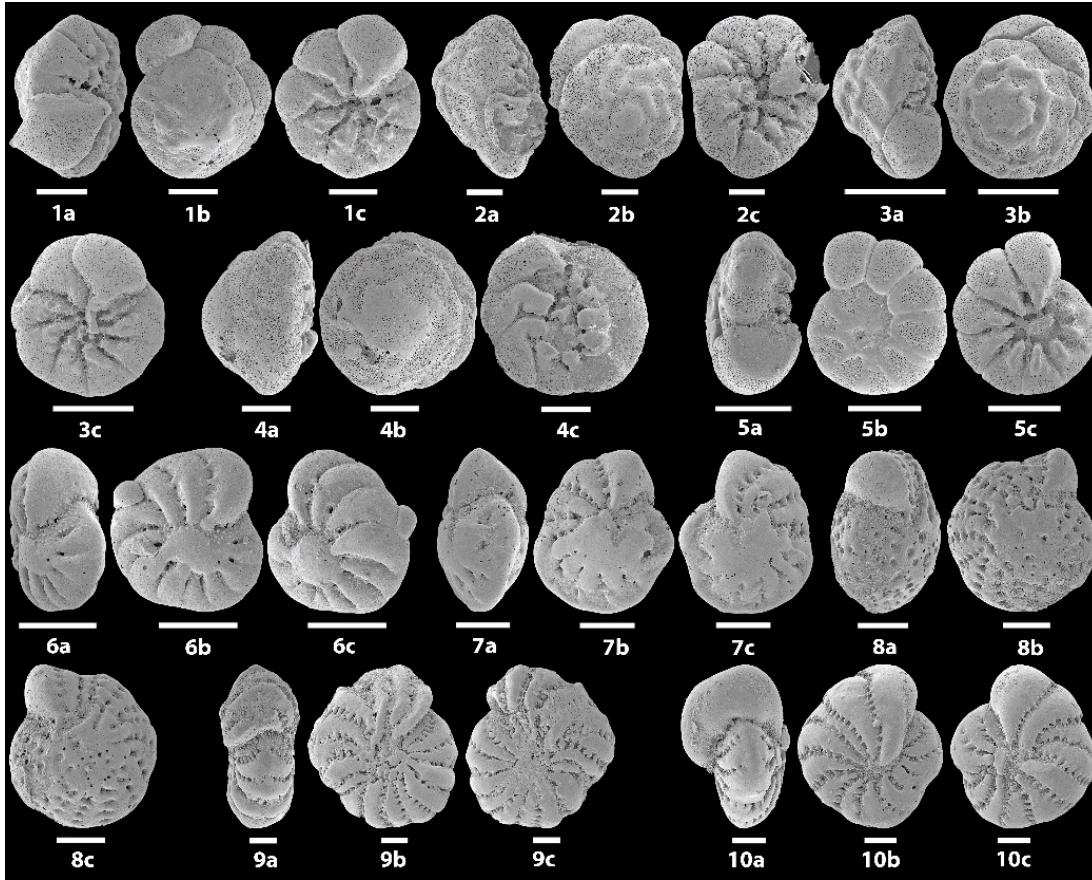


Plate 7

All scale bars are 100 μm . otherwise mentioned on the scale bar

1 a-c *Miliolinella* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, obliterated apertural face and overdevelopment.

2 a-c *Miliolinella* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, wrong coiling mode development.

3 a-c *Miliolinella* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, dented chamber and weird apertural development.

4 a-c *Miliolinella* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, wrong coiling mode development and weird apertural development.

5 a-c *Miliolinella* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, holed chamber and dented.

6 a-c *Spiroloculina* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, weird coiling development.

7 a-c *Quinqueloculina* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, weird coiling orientation and incomplete growth.

8 a-c *Quinqueloculina* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, dented chamber and incomplete growth.

9 a-d *Quinqueloculina* sp., (a) apertural, (b) lateral, and (c) other lateral side view, (d) zoom-in on the strange object, deformed, weird coiling orientation, breakage in certain part, and occurrences of attached epibiont.

10 a-c *Quinqueloculina* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, incomplete growth with strange final chamber positioning and dented chamber.

11 a-c *Quinqueloculina* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, incomplete growth with strange final chamber positioning, dented chamber, and apertural shape modification.

12 a-c *Quinqueloculina* sp., (a) apertural, (b) lateral, and (c) other lateral side view, deformed, modification on coiling mode and orientation.

Plate 7



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Prayudi, S.D., Tawabini, B.S., Amao, A.O., Korin, A., and Kaminski, M.A., 2023. Reviewing the Modern Larger Benthic Foraminifera Diversity and Deformities in the Hypersaline Arabian Gulf: What Do We Know Based on Ecological Updates? The Geological Society of America CONNECTS 2023.

Prayudi, S.D., Tawabini, B.S., Amao, A.O., Arrofi, D., Korin, A., and Kaminski, M.A., 2023. Surface Warming Concerns in the Intertidal Coastal Area of Arabian Gulf and How Resilient the Living Communities Within. The Geological Society of America CONNECTS 2023.

Publications

Prayudi, S.D., Korin, A., and Kaminski, M.A., Thermal tolerance of the shallow-water ostracod Cyprideis in a lagoon in Bahrain, western Arabian Gulf. Arabian Journal for Science and Engineering (Accepted and Waiting for Publication).

Prayudi, S.D., Tawabini, B.S., Korin, A., and Kaminski, M.A., Morphological Deformities in Benthic Foraminiferal Assemblages from Natural Shallow Marine and Lagoonal Environments of the Western Arabian Gulf. Journal of Foraminiferal Research (Under Submission). |