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Distribution of Benthic Foraminifera in Intertidal Sabkha of Al-Kharrar Lagoon, Saudi Arabia: Tools to Study Past Sea-Level Changes

Talha A. Al-Dubai[1,2], Rashad A. Bantan[1], Ramadan H. Abu-Zied[1,3], Aaid G. Al-Zubieri[1,2] and Brian G. Jones[4]*

[1] Marine Geology Department, Faculty of Marine Sciences, King Abdulaziz University, Jeddah, Saudi Arabia, [2] Marine Geology Department, Faculty of Marine Sciences and Environment, Hodeidah University, Al Hudaydah, Yemen, [3] Geology Department, Faculty of Sciences, Mansoura University, Mansoura, Egypt, [4] School of Earth, Atmospheric and Life Sciences, University of Wollongong, Wollongong, NSW, Australia

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***Correspondence:**
Talha A. Al-Dubai
talhadubai@yahoo.com; taldubai@stu.kau.edu.sa

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Contemporary foraminiferal sediment samples were collected from the intertidal sabkha of Al-Kharrar Lagoon, Saudi Arabia, to study the vertical distribution of foraminifers and, based on a modern training set, their potential to develop a predictor of former sea-level changes in the area. Based on hierarchical cluster analysis, the intertidal sabkha is divided into three vertical zones (A, B, and C) represented by three foraminiferal assemblages, where agglutinated species occupied Zone A and calcareous species occupied the other two zones. In Zone A (high intertidal), *Agglutinella compressa, Clavulina angularis* and *C. multicamerata* are dominant species with a minor presence of *Peneroplis planatus, Coscinospira hemprichii, Sorites orbiculus, Quinqueloculina lamarckiana, Q. seminula, Ammonia convexa* and *A. tepida*. In contrast, in Zone B (middle intertidal) the most abundant species are *P. planatus, C. hemprichii, S. orbiculus, Q. lamarckiana, Q. seminula* and *Q. laevigata*, while Zone C (low intertidal) is characterized by *C. hemprichii, Q. costata, S. orbiculus, P. planatus, A. convexa, A. tepida, Spiroloculina communis*, and *S. costigera.* A transfer function for sea-level reconstruction was developed using a modern dataset of 75 contemporary sediment samples and 99 species collected from several transects across the sabkha. The model provided an error of 0.12 m, suggesting that intertidal foraminifers can be used to assess past sea-level changes with high precision in Al-Kharrar Lagoon, and adjacent regions.

Keywords: intertidal sabkha, benthic foraminifera, Red Sea, transfer function, training set, sea-level

INTRODUCTION

Benthic foraminiferal assemblages in sabkhas display discrete vertical zonation within the intertidal zone controlled by a variety of ecological conditions associated with the duration of tidal inundation (Phleger, 1965; Murray, 1971; Scott et al., 1998; Horton, 1999). Tidal inundation not only affects the distribution of foraminiferal assemblages, but also the distribution of vegetation cover and salinity in the intertidal zone (Leorri et al., 2010; Rogers et al., 2017). Accordingly, the distribution of both foraminiferal assemblages and vegetation cover could provide an indication of the intertidal surface elevation since the elevation is directly related to mean sea-level (msl; De Rijk and Troelstra, 1997; Haslett, 2001; Horton and Edwards, 2006). Several authors (Scott and Medioli, 1980a; Scott and Leckie, 1990; Horton and Edwards, 2003, 2006; Leorri et al., 2010) have indicated a close relationship between the vertical distribution of foraminiferal assemblages and the intertidal surface elevation. However, there are different opinions regarding the effect of elevation on intertidal foraminiferal distributions (Horton et al., 1999; Horton and Edwards, 2006).

Recent studies have suggested that intertidal foraminifers are controlled by environmental variables such as salinity and flooding frequency rather than their elevation with respect to mean-tide level (De Rijk, 1995; De Rijk and Troelstra, 1997; Punniyamoorthy et al., 2021). In some areas, salinity appears to be the most important factor influencing the distribution of foraminifers, while the microfaunal-elevation relationships are not of worldwide significance (De Rijk, 1995; Hayward et al., 2004; Lal et al., 2020). Intertidal foraminifers tolerate a wide variety of daily and seasonal changes in the environmental conditions, which are reflected in their increase or decrease in abundance and diversity (Leorri et al., 2010).

Calcareous and agglutinated taxa are found in intertidal environments and their abundance varies from site to site according to different environmental conditions such as salinity, oxygen and alkalinity (Lal et al., 2020) and elevation (Horton and Murray, 2007). Calcareous species predominated in the lower intertidal sabkha with normal salinity, while agglutinated species predominated in middle and higher intertidal sabkha areas where salinity is more variable (Hayward, 1993; Hayward and Hollis, 1994; De Rijk, 1995; Culver et al., 2012; Strachan et al., 2015; Lal et al., 2020). Alkalinity also plays an essential role in the foraminiferal distribution in the intertidal sabkha, where calcareous tests are susceptible to dissolution at low pH conditions < 7.8 and can completely disappear at ~ 7.6 (Dias et al., 2010); however, agglutinated shells are more resistant and dominate the foraminiferal assemblage under conditions where pH ≤ 7.6 (Scott and Medioli, 1978; Edwards and Horton, 2000; Sanders, 2003; Hayward et al., 2004, 2015; Woodroffe et al., 2005; Dias et al., 2010).

Preservation of the foraminiferal assemblages in intertidal sabkhas is of great importance in palaeoenvironmental interpretations of older deposits (Cearreta and Murray, 2000; Leorri and Cearreta, 2004). Moreover, benthic foraminifers have been widely used as bio-indicators for determining intertidal surface elevations and also past sea-level changes, since the foraminifers respond strongly to both changes in elevation above msl and salinity (Gehrels, 1994; Cearreta and Murray, 2000; Horton and Edwards, 2006; Leorri et al., 2008b; Abu-Zied and Bantan, 2013).

Reconstructing intertidal surface elevations is done by developing a transfer function(TF) using a modern training dataset comprising of faunal data (relative abundance within a benthic foraminiferal assemblage) and the environmental data such as elevation and salinity (Imbrie, 1971; Birks, 1995). A better understanding of the nature of the relationship between foraminiferal data and environmental data enhances the precision and accuracy of a sea-level reconstruction and thus to the quality of the study (Horton et al., 1999). This relationship can be quantified in modern intertidal environments using regression model analysis (Cahill et al., 2015). Several models have been used in studies of sea-level changes, including: unimodal (WA-PLS) or linear models (PLS), and the most appropriate model for any study is determined based on the species–environment response model (Birks, 1995).

Over the past four decades, benthic foraminiferal data have been used to better understand and reconstruct past sea-level changes for many areas, including Australia, Europe, Britain, North America, and recently the Saudi Arabian Red Sea coast (Shennan et al., 1996; Horton et al., 1999; Edwards and Horton, 2000; Leorri et al., 2008a, 2010; Woodroffe, 2009; Callard et al., 2011; Abu-Zied and Bantan, 2013; Kemp et al., 2013; Strachan et al., 2014; Ghandour et al., 2021). This is because the distribution of foraminifers is controlled by the frequency and duration of inundation, which is fundamentally a function of tidal elevation (Scott and Medioli, 1978; Horton and Edwards, 2006; Kemp et al., 2013). Published studies using foraminifera-based transfer functions in the Red Sea are very scarce, except for the studies by Abu-Zied and Bantan (2013, 2015) at Shuaiba Lagoon, 80 km south of Jeddah city. Previously published works on the Saudi Red Sea coast have not attempted to investigate the vertical zonation of foraminiferal assemblages in the intertidal sabkha zone. Therefore, in this study, we focus on several points: (i) to investigate the distribution of modern foraminifers across the intertidal sabkha of the Al-Kharrar Lagoon (KL) to determine whether the foraminiferal assemblages display evidence of vertical zonation; (ii) to explain the relationship between the foraminifera distribution and environmental variables such as elevation and salinity; and (iii) to present new foraminiferal data to develop a predictor that can be used to assess former sea-level changes in the area and adjacent regions.

STUDY AREA

The Al-Kharrar Lagoon is located 10 km northwest of Rabigh city, Saudi Arabia, on the eastern coast of the Red Sea (**Figure 1**), between 22.83° to 23°N and 38.81° to 38.97°E. The lagoon occurs in a relatively stable part of the coastal plain, known as the Tihamah plain, where tectonic uplift has been almost negligible or uncertain during the Pliocene and Pleistocene periods (Lambeck, 1995; Plaziat et al., 2008; Manaa et al., 2016). Al-Kharrar Lagoon is a small (74 km^2), semi-enclosed shallow basin with an average depth of 5 m (Al-Dubai et al., 2017b), elongated parallel to the sea (about 20 km long and 4 km wide). It probably formed by erosion during the Late Pleistocene glacial sea-level low stand, and was then drowned during the post-glacial sea-level rise, especially in the early Holocene transgression (Braithwaite, 1987; Brown et al., 1989). The southern and eastern sides of the Al-Kharrar Lagoon are bounded by extensive sabkhas, mainly composed of alluvial sand, evaporite deposits, and bioclastic fragments, and are dominated by green cyanobacteria, mangrove trees (*Avicennia marina*) and macroalgae (Al-Dubai et al., 2017b). In contrast, the western side is bordered by old, raised limestone reef terraces (1–3 m

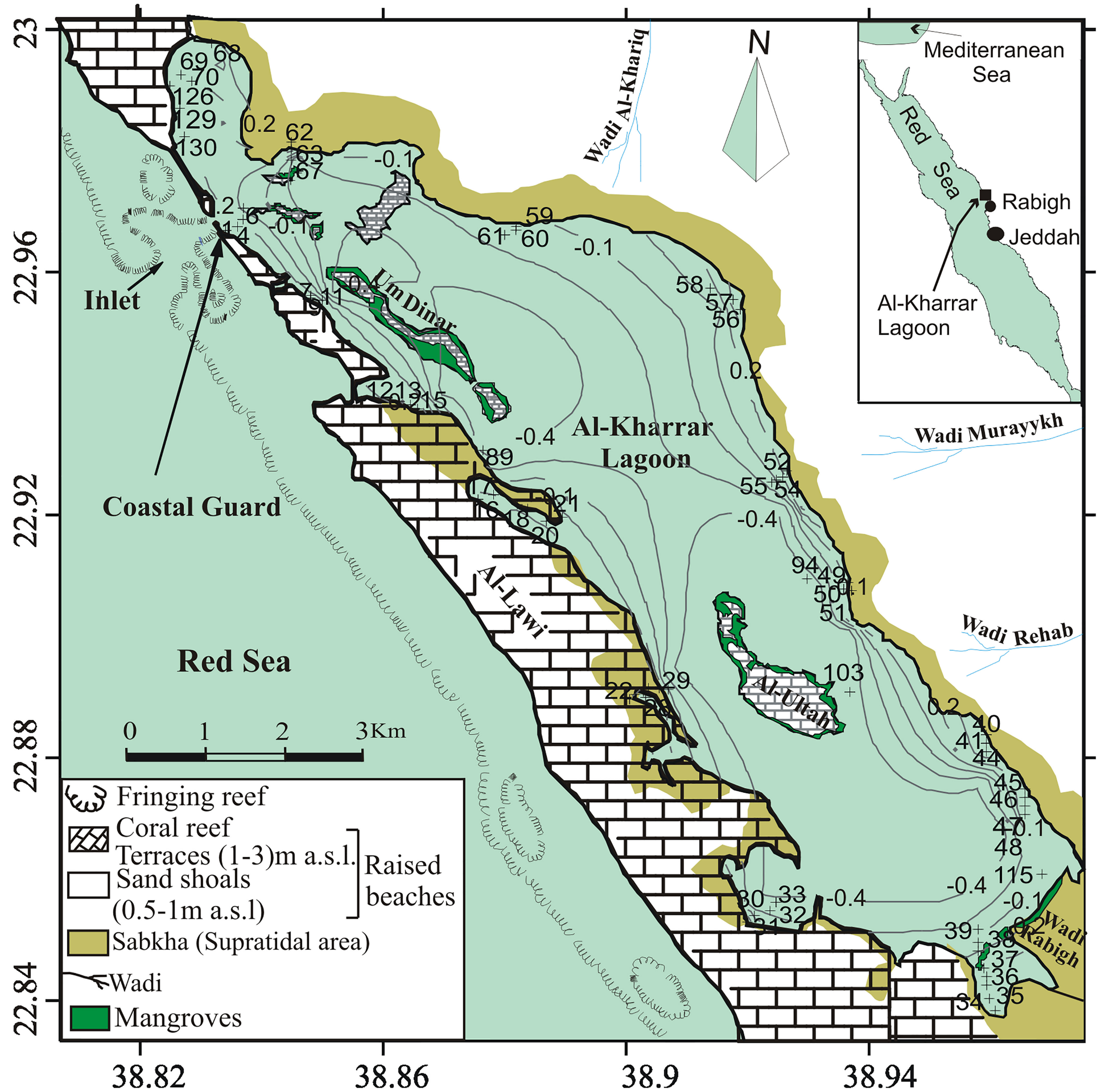

FIGURE 1 | Location map of supratidal–intertidal sabkha, surface sediment sample sites (transects) and elevations in the Al-Kharrar Lagoon during March 2014 (modified after Al-Dubai et al., 2017a).

above msl) of Pleistocene age (Al-Sayari and Zötl, 1978; Basaham, 2008). The lagoon connects with the adjacent Red Sea *via* a very narrow inlet (about 120 m wide and 14 m deep) that allows stratified water bodies to pass through (Al-Dubai et al., 2017b). One layer enters the lagoon as a surface inflow with temperatures between 25 and 30°C in winter and summer, respectively, while the salinity remains constant at 39‰. A second layer leaves the lagoon through its narrow inlet as a subsurface outflow with temperatures of 24.5 and 30°C and salinities of 39.8 and 40.5‰ during winter and summer, respectively (Al-Dubai et al., 2017b). This water exchange with the Red Sea is mainly governed by thermohaline circulation, the tidal force, and the local NNE wind that dominates the area throughout the year (Al-Barakati, 2010; Al-Dubai et al., 2017b). The tidal range on the coast of Rabigh city (0.71 m) varies from the highest astronomical tide (0.39 m HAT above msl) to the lowest astronomical tide (–0.32 m LAT below msl; Saudi Aramco Tide Tables 2014), whereas the daily tidal range in KL is about 0.24 m (Al-Dubai, 2019). The latter is similar to that recorded in the Jeddah area due to its location near the nodal points located in the central Red Sea (Morcos, 1970; Gharbi et al., 2018), with ranges between 0.20 and 0.30 m during a spring-neap cycle (Lisitzin, 1974), that is generated by the semi-diurnal tidal force (Al-Barakati, 2010). The Al-Kharrar Lagoon has a warm, dry tropical climate with scarce rainfall (between 50–100 mm/year), high evaporation rates of up to 2 m/year (Sofianos et al., 2002; Bantan et al., 2020) and no perennial river runoff.

TABLE 1 | Sample sites, elevations, physico-chemical parameters, and carbonate and organic matter contents in surface sediments of Al-Kharrar Lagoon during March 2014 (modified after Al-Dubai et al., 2017a,b).

Sample no	Lat N	Long. E	Elevation (m)	Temp. (°C)	Salinity (‰)	Dissolved oxygen (mg/l)	pH	CaCO3 (%)	Organic matter (%)	Substrate macro-fauna and flora
KHA 1	22.9657	38.8358	0.48	32.16	38.89	6.67	8.27	57.8	17.96	Firm, algal-mat and coastal shrubs
KHA 2	22.9661	38.8361	0.31	29.37	38.69	7.38	8.21	92.5	6.11	Firm, algal-mat and mangrove
KHA 3	22.9672	38.8365	0.18	28.59	37.64	7.38	8.23	90.1	7.24	Hard and Filamentous algae
KHA 4	22.9681	38.8366	0.19	28.61	38.54	6.98	8.23	91.4	4.51	Hard and Filamentous algae
KHA 5	22.9690	38.8367	0.135	28.89	38.40	7.57	8.26	92	4.18	Hard and Filamentous algae
KHA 6	22.9694	38.8365	–0.02	28.93	38.71	7.91	8.28	90.4	4.93	Hard
KHA 7	22.9550	38.8491	0.47	29.99	40.53	6.22	8.26	63.4	23.03	Firm and coastal shrubs
KHA 8	22.9552	38.8492	0.22	30.35	40.12	7.52	8.20	86.1	5.09	Firm and algal
KHA 9	22.9558	38.8499	–0.04	28.98	40.48	6.33	8.11	86	3.58	Soft
KHA 10	22.9564	38.8504	–0.36	28.41	40.47	6.24	8.10	88.5	3.43	Soft
KHA 11	22.9568	38.8511	–0.43	27.81	40.38	5.93	8.07	91.9	5.41	Soft
KHA 12	22.9368	38.8656	0.357	29.92	41.10	7.73	8.29	89.7	5.63	Soft
KHA 13	22.9378	38.8663	0.112	29.12	41.11	6.51	8.22	93.1	8.38	Soft
KHA 14	22.9388	38.8670	0.09	29.17	41.10	6.29	8.11	95.5	5.42	Soft and mucous algal-mats
KHA 15	22.9395	38.8678	–0.38	28.68	40.80	6.09	8.11	86.6	7.53	Soft
KHA 16	22.9180	38.8817	0.35	26.29	53.11	7.12	8.82	66	15.51	Soft and algal-mats
KHA 17	22.9188	38.8828	0.33	28.59	45.91	7.61	9.04	71.5	25.35	Algal-mats and coastal shrubs
KHA 18	22.9200	38.8843	0.12	27.55	43.96	6.86	8.84	72.2	10.03	Soft and mucous algal-mats
KHA 19	22.9221	38.8867	0.37	23.68	53.64	5.28	8.96	73.7	27.23	Soft and mucous algal-mats
KHA 20	22.9228	38.8877	0.165	25.85	41.41	6.13	8.20	81.5	7.53	Hard
KHA 21	22.9230	38.8884	–0.05	27.20	40.61	5.93	8.14	89.9	3.70	Firm
KHA 22	22.8901	38.8991	0.52	26.54	45.28	7.21	8.67	64	24.39	Algal-mats (Supratidal)
KHA 23	22.8909	38.9008	0.41	25.03	43.24	5.99	8.75	90.1	4.40	Algal-mats (Supratidal)
KHA 24	22.8922	38.9031	0.55	28.98	42.79	8.56	8.55	65.7	22.85	Algal-mats (Supratidal)
KHA 25	22.8934	38.9042	0.39	26.10	40.84	6.18	8.14	82.6	8.65	Firm (Supratidal)
KHA 26	22.8935	38.9047	0.122	25.76	40.42	5.11	8.14	88	4.50	Hard (Supratidal)
KHA 27	22.8937	38.9054	0.005	26.30	40.17	5.57	8.16	91.6	3.63	Firm and seagrasses (Supratidal)
KHA 28	22.8940	38.9063	–0.14	26.76	40.11	5.50	8.15	87.2	4.06	Firm and seagrasses (Supratidal)
KHA 29	22.8939	38.9066	–0.36	26.60	40.09	5.67	8.14	94.8	4.70	Firm and seagrasses (Supratidal)
KHA 30	22.8540	38.9187	0.377	29.31	41.72	7.24	8.17	79.4	15.25	Algal-mats and shrubs (Supratidal)
KHA 31	22.8545	38.9192	0.195	27.70	41.56	5.64	8.10	86.1	7.36	Soft
KHA 32	22.8552	38.9202	–0.02	27.07	41.47	5.80	8.13	92.6	4.77	Hard
KHA 33	22.8555	38.9207	–0.37	27.12	41.41	5.61	8.12	85.6	7.20	Soft
KHA 34	22.8383	38.9603	0.43	30.98	51.64	6.1	8.93	16.9	7.38	Thick algal-mats
KHA 35	22.8436	38.9598	0.36	31.26	44.19	8.92	8.82	28.9	8.06	Soft and algal-mats (Supratidal)
KHA 36	22.8457	38.9595	0.185	31.00	45.23	9.62	8.90	11.4	5.13	Soft in tidal creek
KHA 37	22.8492	38.9590	0.02	29.19	42.18	5.91	8.23	8.7	3.13	Firm
KHA 38	22.8502	38.9581	–0.12	28.62	42.23	5.75	8.21	12.9	3.00	Firm
KHA 39	22.8516	38.9564	–0.24	28.57	41.93	5.98	8.12	9.3	2.69	Firm
KHA 41	22.8797	38.9597	0.425	24.32	45.76	4.76	7.91	6.7	3.01	Algal-mats (supratidal)
KHA 42	22.8783	38.9599	0.06	26.20	41.36	4.66	8.12	9.8	1.85	Firm
KHA 43	22.8777	38.9598	–0.07	27.20	41.41	4.38	8.16	13.4	2.20	Firm and seagrasses
KHA 44	22.8762	38.9600	–0.38	26.84	41.39	4.38	8.16	16.5	2.68	Firm and seagrasses
KHA 45	22.8702	38.9667	0.41	26.85	41.81	5.75	8.20	9.6	4.86	Soft
KHA 46	22.8697	38.9659	0.075	26.64	41.63	5.16	8.20	14.7	1.94	Firm and small mollusks
KHA 47	22.8694	38.9653	–0.18	26.86	41.39	5.79	8.20	13.4	1.87	Firm and algae
KHA 48	22.8692	38.9651	–0.32	27.02	41.23	5.97	8.19	13.4	2.92	Firm and seagrasses
KHA 49	22.9018	38.9385	0.46	28.54	39.69	5.62	8.17	35.8	2.43	Firm
KHA 50	22.9016	38.9384	–0.03	27.58	40.78	6.08	8.17	18.8	6.06	Soft
KHA 51	22.9014	38.9383	–0.47	27.25	40.67	5.87	8.15	17.6	3.42	Firm
KHA 52	22.9217	38.9292	0.53	30.22	41.05	7.25	8.23	42.1	2.10	Sand and beach-rock

(Continued)

TABLE 1 | (Continued)

Sample no	Lat N	Long. E	Elevation (m)	Temp. (°C)	Salinity (‰)	Dissolved oxygen (mg/l)	pH	CaCO3 (%)	Organic matter (%)	Substrate macro-fauna and flora
KHA 53	22.9213	38.9286	–0.06	27.81	40.41	5.75	8.14	32.3	4.15	Sand and beach-rock
KHA 54	22.9212	38.9283	–0.02	28.11	40.35	6.21	8.17	33.6	16.88	Soft
KHA 55	22.9208	38.9276	–0.35	27.53	40.29	5.81	8.15	49.9	3.54	Hard and Turbinaria
KHA 56	22.9549	38.9189	0.498	34.57	46.14	7.98	8.77	11.6	4.93	Algal-mat
KHA 57	22.9542	38.9182	0.475	30.57	40.40	6.19	8.15	21.4	3.61	Algal-mat
KHA 58	22.9537	38.9165	0.042	28.54	40.16	6.19	8.14	26.9	3.72	Firm to hard
KHA 59	22.9685	38.8785	0.485	31.83	38.32	6.18	8.18	30	2.68	Beachrock
KHA 60	22.9679	38.8784	–0.12	28.69	39.87	6.31	8.15	32.8	2.72	Firm
KHA 61	22.9671	38.8780	–0.18	27.87	39.79	6.02	8.16	43.2	4.06	Firm to hard
KHA 62	22.9805	38.8445	0.48	30.85	40.87	7.10	8.64	26.6	4.40	Firm and algal-mat
KHA 63	22.9802	38.8445	0.198	30.44	39.84	6.65	8.22	48.6	5.42	Soft and mangrove
KHA 64	22.9796	38.8444	0.095	29.56	39.75	6.20	8.20	70.8	6.56	Soft and mangrove
KHA 65	22.9792	38.8443	0.04	29.53	39.71	6.25	8.20	73.5	7.42	Soft and mucous algal-mats
KHA 66	22.9789	38.8444	–0.415	29.12	39.63	6.35	8.22	73.1	6.31	Soft
KHA 67	22.9789	38.8433	0.08	29.33	39.72	6.02	8.21	77.6	7.35	Soft and mangrove
KHA 68	22.9971	38.8346	0.52	27.93	44.80	6.47	9.26	21.3	7.33	Thick algal-mat
KHA 69	22.9957	38.8341	0.36	29.17	42.73	7.15	8.44	57.3	12.29	Soft
KHA 70	22.9946	38.8334	0.28	29.23	41.96	7.03	8.34	52.9	6.99	Soft
KHA 71	22.9935	38.8328	–0.16	28.47	41.61	5.83	8.27	52	14.83	Soft
KHA 89	22.9309	38.8771	–0.51	23.48	39.58	7.28	8.35	92.2	5.48	Soft
KHA 94	22.9077	38.9324	–0.5	25.99	40.53	7.22	8.37	46.4	7.03	Soft
KHA 103	22.8842	38.9431	–0.09	24.97	41.22	7.42	8.39	75.8	5.98	Soft and seagrasses
KHA 115	22.8644	38.9665	–0.26	22.70	41.59	6.69	8.35	11.9	3.90	Soft (Black color)
KHA 126	22.9945	38.8336	0.46	29.26	45.37	5.98	8.42	27.1	10.92	Soft, *Avrainvillea* and *Caulerpa*
KHA 127	22.9938	38.8332	0.38	26.66	42.97	10.03	8.63	62.3	8.50	Soft and *Avrainvillea* algae
KHA 128	22.9931	38.8324	0.34	26.92	42.26	8.96	8.65	67.5	8.70	Soft and *Avrainvillea* algae
KHA 129	22.9862	38.8295	0.15	26.33	42.23	7.08	8.42	51	5.02	Soft and seagrasses
KHA 130	22.9866	38.8301	0.055	25.83	40.56	7.57	8.40	74.4	3.89	Soft

MATERIALS AND METHODS

Field Sampling and Elevations

Seventy-five contemporary foraminiferal samples were collected along several elevational transects across the supratidal–intertidal sabkha of KL in March 2014. Sediment samples were collected at ∼50 m horizontal intervals within floral communities using a hand scoop, and were located between 0.6 and –0.5 m with respect to the mean tidal level (**Figure 1**). The locations of the sediment samples were determined using a Garmin GPS. The physico-chemical parameters temperature, salinity, pH and dissolved oxygen of the bottom waters were measured *in situ* using a YSI 556 MPS Multi-parameter meter and are listed in **Table 1** and presented in **Figure 2**. Each sediment sample site in the transects was surveyed to a known reference height enabling each sample to be related to the local Saudi tidal datum (local lowest astronomical tide, LAT, which is 32 cm below msl) and the tidal elevation at each site was estimated using the Saudi Tide Tables (Saudi Aramco Tide Tables, 2014; see **Table 2**). Local LAT is considered as a reference to measure the daily tidal range along the Jeddah coast. Therefore, the elevation of the sample sites relative to LAT is equal to the measured water depth minus the tidal elevation at the time of sampling. Sampling was also focused on the vegetated intertidal zone above mean high water (MHW), since this is the main environment analyzed for sea-level studies (Gehrels and van de Plassche, 1999). Hence, data obtained from all transects were combined to establish a training set of supratidal–intertidal benthic foraminifers.

Foraminiferal Analysis

The uppermost layer (∼1 cm) from each sediment sample was scraped off and partitioned into two aliquots: one set of subsampled sediments was stored in numbered polyethylene jars, stained with buffered Rose Bengal solution (1.5 g of Rose Bengal powder for every liter of 95% ethyl alcohol), and then transported to the laboratory and preserved for several days prior to micropaleontologic analysis following (Abu-Zied et al., 2007, 2016). The Rose Bengal was used to distinguish between living (stained) and dead foraminifers (Murray, 1991) as it stains the cytoplasm of foraminifers alive at the time of collection (Walton, 1952), or which died in the last period of weeks to months (Bernhard, 1988; Corliss and Emerson, 1990) while the non-degraded proteins are still stainable (Barras et al., 2014). This makes it difficult to determine which were living at the time of sampling (Horton and Edwards, 2003), and thus overestimates the living assemblages (Schönfeld et al., 2012).

TABLE 2 | (A) Tide levels at Al-Kharrar Lagoon (Rabigh) relative to the Saudi datum (Saudi Aramco Tide Tables, 2014), **(B)** coastal vegetation on the supratidal intertidal sabkha of Al-Kharrar Lagoon.

A

Tide level	Height (cm)
Highest High Tidal Water (HHTW)	66
Mean High Tidal Water (MHTW)	56.1
Tidal range	23.9
Mean Low Tidal Water (MLTW)	32.3
Lowest Low Tidal Water (LLTW)	24
Lowest Astronomical Tide (LAT)	32
Highest Astronomical Tide (HAT)	39

B

Elevations (m)	Coastal vegetation	Floral zone
1	*Avicennia marina*	Supratidal-high intertidal
1	*Salicornia fruticosa*	Supratidal-high intertidal
0.5	*Avrainvillea* cf. *A. amadelpha*	High intertidal
0.3 to –0.5	*Cymodocea rotundata*	Middle-low intertidal
–0.4 to –4	*Halophila stipulacea*	Low intertidal-subtidal

Therefore, individuals showing a clear pink (or red) color in the last few chambers were counted as living fauna at time of collection, whereas colorless empty tests were counted as dead (Walton, 1952; Murray, 1991; De Stigter et al., 1998, 1999). The living faunal assemblage was not used in this study because it is influenced by seasonal environmental changes; consequently, they show a seasonal bias when used in palaeoenvironmental reconstructions. In contrast, the dead species represent a time-averaged accumulation of foraminiferal tests, therefore, they are considered to be a better analog for palaeoenvironmental reconstructions (Murray, 1991; Horton and Edwards, 2006).

The second set of subsampled sediments was used for geochemical analysis, such as organic matter and carbonate content. In the laboratory, each sample was oven-dried at 50°C for 24 h and weighted. They were then gently rinsed and washed through 2 and 0.063 mm sieves to remove any excess stain and mud material and to separate gravel (>2 mm) and sand (0.063–2 mm) fractions. The residual fractions obtained in each sieve were re-dried at 50°C and weighed again to determine their percentages using the total dry weight of the sample (Abu-Zied et al., 2007; Frontalini et al., 2013; for further details see Al-Dubai et al., 2017a). The 2–0.063 mm fraction was divided by a splitter to sub-fractions to use in quantitative analysis of benthic foraminifers. Modern benthic foraminiferal tests were picked, counted and identified under a binocular microscope from a known fraction of sampled sediment. Only relative faunal abundances of the death assemblage were used to produce and improve the performance of the transfer function (Leorri et al., 2008b). Several references (Loeblich and Tappan, 1987; Haig, 1988; Abu-Zied et al., 2007, 2013, 2016; Al-Dubai et al., 2017a) were used to aid in taxonomic identifications of benthic foraminiferal species found along the transects. The flora cover in the supratidal–intertidal sabkha along the transects (**Figure 3**) was identified and listed in **Table 2** (for more details about the flora see Al-Dubai et al., 2017a).

Organic matter content (LOI) was determined by the loss-on-ignition (LOI) technique on dry bulk sediment samples at 550°C following Heiri et al. (2001) and Abu-Zied et al. (2016). Carbonate content ($CaCO_3$) was determined by loss of weight following Basaham and El-Sayed (1998) and Al-Dubai et al. (2017a).

Statistical Analysis

The relative abundance of modern benthic foraminifers was plotted as percentages against elevation (cm, LAT) above the Saudi datum (Saudi Aramco Tide Tables, 2014). Cluster analysis was applied using Primer v. 5.0 (Clarke and Warwick, 1994), to help interpret the relationship between the modern foraminiferal assemblage and elevation. Hierarchical cluster analysis was applied using group-average linking of Euclidean distance coefficients of Log (x + 1) transformed, standardized species data from the total death assemblage. The transfer function was applied to the relative abundance of modern foraminifers from the KL using the software package C^2 (Juggins, 2007), to quantify the relationship of the contemporary benthic foraminifers with site elevations in the intertidal area. Knowledge of environmental gradient lengths is also very important to determine whether linear-based or unimodal-based statistical methods are appropriate in the study (Birks, 1995). This was estimated using Detrended correspondence analysis (DCA) in PAST software version 2 (Hammer et al., 2001). DCA with detrending by segments was applied to determine the elevational gradient lengths of modern foraminiferal training sets in terms of standard deviation (S.D.) units (Birks, 1995). Thus, the training set of death assemblages with elevation has produced a gradient length of 4.8 S.D. units. Hence a unimodal-based method of regression was used to calculate regression statistics, as it is recommended for training datasets with gradient lengths greater than two S.D. units (Birks, 1995). The best regression model for the training datasets was performed using the weighted-averaging partial least squares (WA-PLS) with the leave-one-out cross validation method ("jack-knifing"; Edwards et al., 2004; Callard et al., 2011; Abu-Zied et al., 2013) and log10-transformed species data. Jack-knifing ($RMSEP_{Jack}$) is a measure of the overall predictive abilities of the dataset. Component 3 in the models from the training dataset was chosen for this study, because it is yielded the smallest RMSEP errors in elevation reconstruction, low maximum bias, and the highest coefficients of determination ($r^2{}_{jack}$) for observed vs. predicted values (**Table 4**). The overall performance of each transfer function model was assessed in terms of RMSEP, r^2 of observed vs. predicted values, and maximum bias since and they are considered to be measures of the overall predictive abilities of the modern training set (Birks, 1995; Horton, 1999; Horton et al., 1999; Horton and Edwards, 2006; Massey et al., 2006; Leorri et al., 2008b; Callard et al., 2011). This allows comparisons among transfer functions (Gasse et al., 1995). In the training set used for the model, outliers were excluded because they showed weak relationships with elevation, and this, in turn, will increase the predictive ability of the training set (Gasse et al., 1995; Jones and Juggins, 1995).

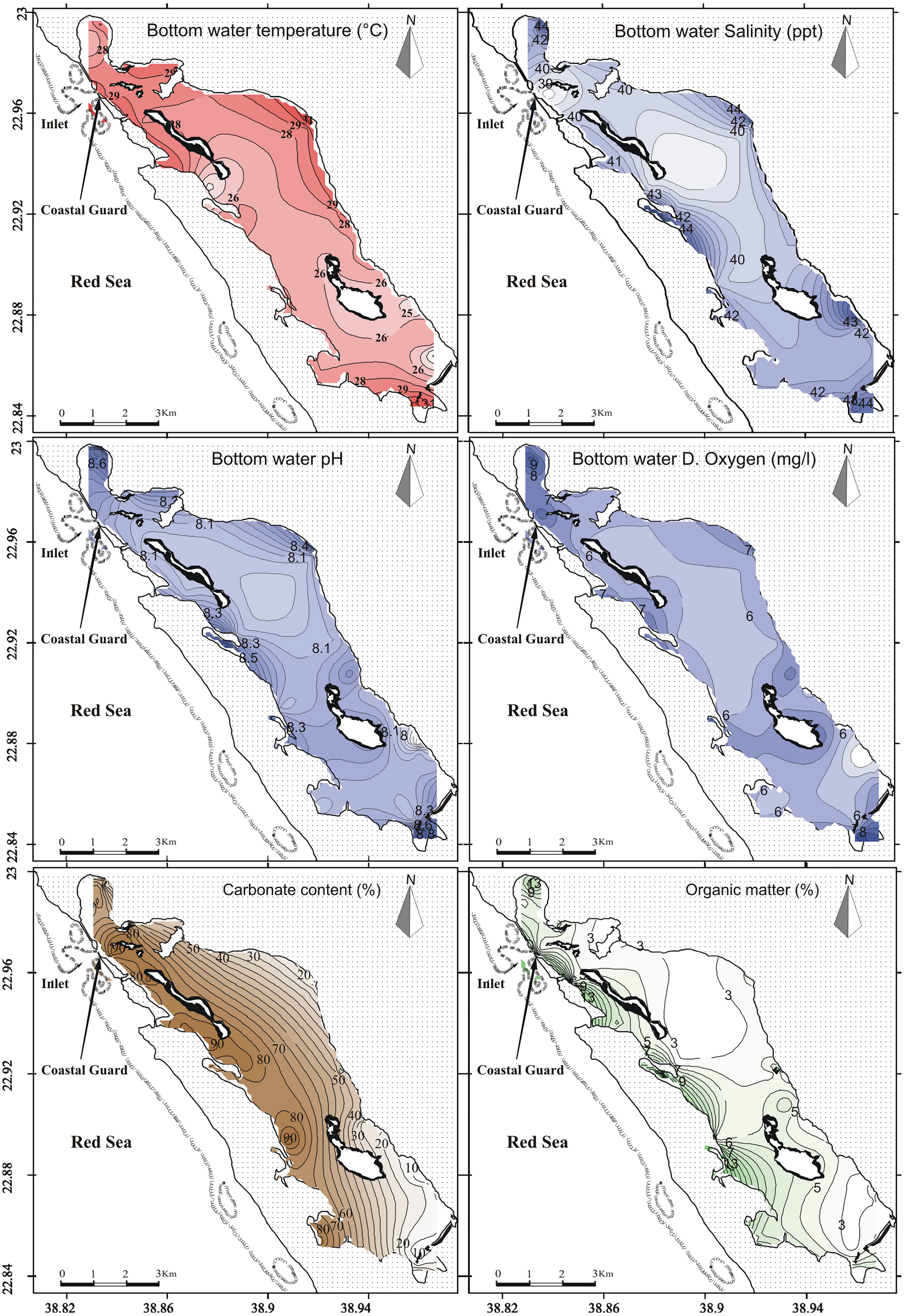

FIGURE 2 | Spatial distribution of physico-chemical parameters (bottom temperature, bottom salinity, bottom pH and bottom dissolved oxygen), carbonate and organic matter contents in the Al-Kharrar Lagoon during winter 2014.

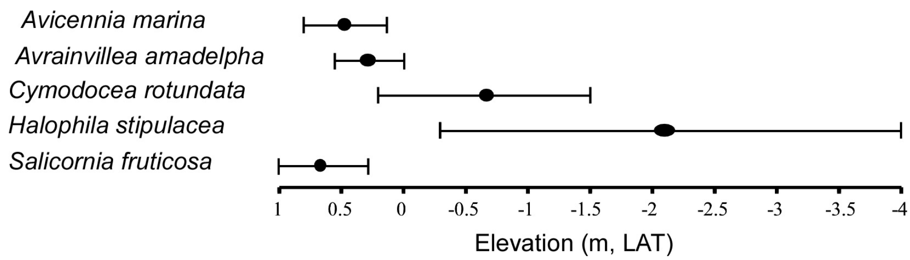

FIGURE 3 | Vegetation zonation along the transects across the intertidal sabkha vs. the elevation (m, LAT) of the Al-Kharrar Lagoon during March 2014.

RESULTS

Physico-Chemical Parameters

Overall, the water elevation in the KL ranges from 0.5 m in the southern part 0 to −18 m at the inlet (**Figure 1**), it then deepens gradually to more than −18 m toward the outer part of the lagoon inlet. However, the studied samples were collected from intertidal zones to depths of up to 0.5 (**Figure 1**). The bottom water temperature decreased from 29°C in the northern part (inlet) to 26°C at the southern part of the lagoon, with an average of 27°C. Then, it increased to 31°C in the supratidal areas of the lagoon that were covered by a thin (∼10 cm) layer of water during the sampling time (**Figure 2**). In contrast, the bottom water salinity increased from 39 ‰ at the inlet to 42 ‰ in the southern part of the lagoon, with a mean value of 41 ‰. Then, it increased to 44 ‰ in the very shallow areas of the lagoon (**Figure 2**). The bottom water pH varied from 8.1 at the inlet to 8.3 in the shallowest areas at the southern part of the lagoon, with a mean value of 8.2. Then, it increased to 8.8 in the very shallow areas of the lagoon (**Figure 2**). The bottom water dissolved oxygen ranged from 6 mg/l at the northern part to 7 mg/l at the southern part of the lagoon (sheltered areas), with an average of 6.4 mg/l. Then, it increased to 9 mg/l in the very shallow areas of the lagoon (**Figure 2**).

Organic Matter and Carbonate Content

The organic matter predominates in the western and southern parts of the lagoon (up to 13%) where extensive intertidal sabkhas are present; whereas it decreases significantly toward the eastern side of the KL, reaching 3% at the shoreline (**Figure 2**).

The carbonate content predominates in the western side of the lagoon (up to 85%) where it is bordered by old, raised reefal limestone terraces. It decreases significantly toward both the southern and eastern parts (down to15%), while the clastic materials dominate these parts (**Figure 2**).

Coastal Vegetation

Al-Kharrar sabkha generally displays several zones, including supratidal, intertidal and subtidal zonations based on the vegetation present along transects across the sabkha flats. However, these zones can be divided into smaller zones based on elevation and vegetation, including supratidal, high intertidal, middle intertidal, low intertidal and high subtidal (**Figure 3** and **Table 2**). The supratidal-high intertidal areas constitute 80% of the KL forming a belt around the lagoon with dense vegetation cover. The supratidal-high intertidal sabkha is covered by a thin layer of seawater at high tide and is dominated by mangrove (*Avicennia marina)* and *Salicornia frulticame*, which are more prevalent than other plants and have a moderate tolerance to high salinity (**Figure 3**). The middle intertidal area is occupied by *Avrainvillea* cf. *A. amadelpha,* which forms dense patches growing on coral rubble covered by silt and sand. Low intertidal and high subtidal areas predominantly contain seagrass, such as *Cymodocea rotundata* and *Halophila stipulacea,* which represent suitable habitats for many faunas including the larger foraminifer *Sorites orbiculus* that attaches its test as a white spot on the seagrasses (**Figure 4**).

Dead Foraminiferal Assemblage

Intertidal benthic foraminiferal species were relatively abundant and well-preserved at all elevations on the intertidal sabkha, with the exception of some samples from the high supratidal area where they are characterized by very low faunal abundance and diversity (i.e., only one or two species in each sample), which reflects the marginal marine nature of the upper limit of intertidal-supratidal environments. A total of 99 dead species, exceeding approximately 60% of the total assemblage, were identified across the intertidal sabkha of KL (**Figure 5**). Only 4 dead agglutinated species were present, and the rest were calcareous (porcelaneous and hyaline) species (**Figure 6** and **Table 3**).

Along several transects across the intertidal sabkha, cluster analysis divided the intertidal sabkha into three zones (A, B, and C) based on the dominant species, and these divisions were remarkably consistent with the geomorphological and vegetative zones. Assemblages in Zone A differ from the assemblages in the rest of the zones. Zone A is characterized by the presence of agglutinated species such as *Agglutinella compressa, Clavulina angularis* and *Clavulina frulticamerate* albeit in low abundances. Moreover, calcareous species were present in moderate abundance in this zone, including *Peneroplis planatus, Coscinospira hemprichii, Sorites orbiculus, Quinqueloculina lamarckiana, Quinqueloculina seminula, Ammonia convexa, Ammonia tepida* and *Quinqueloculina laevigata.* Zone **A** extends from 0.6 to 0.5 m above LAT and contains very specific vegetation (e.g., *Avicennia marina, Salicornia ?ulticame* and *Avrainvillea* cf. *A. amadelpha*.

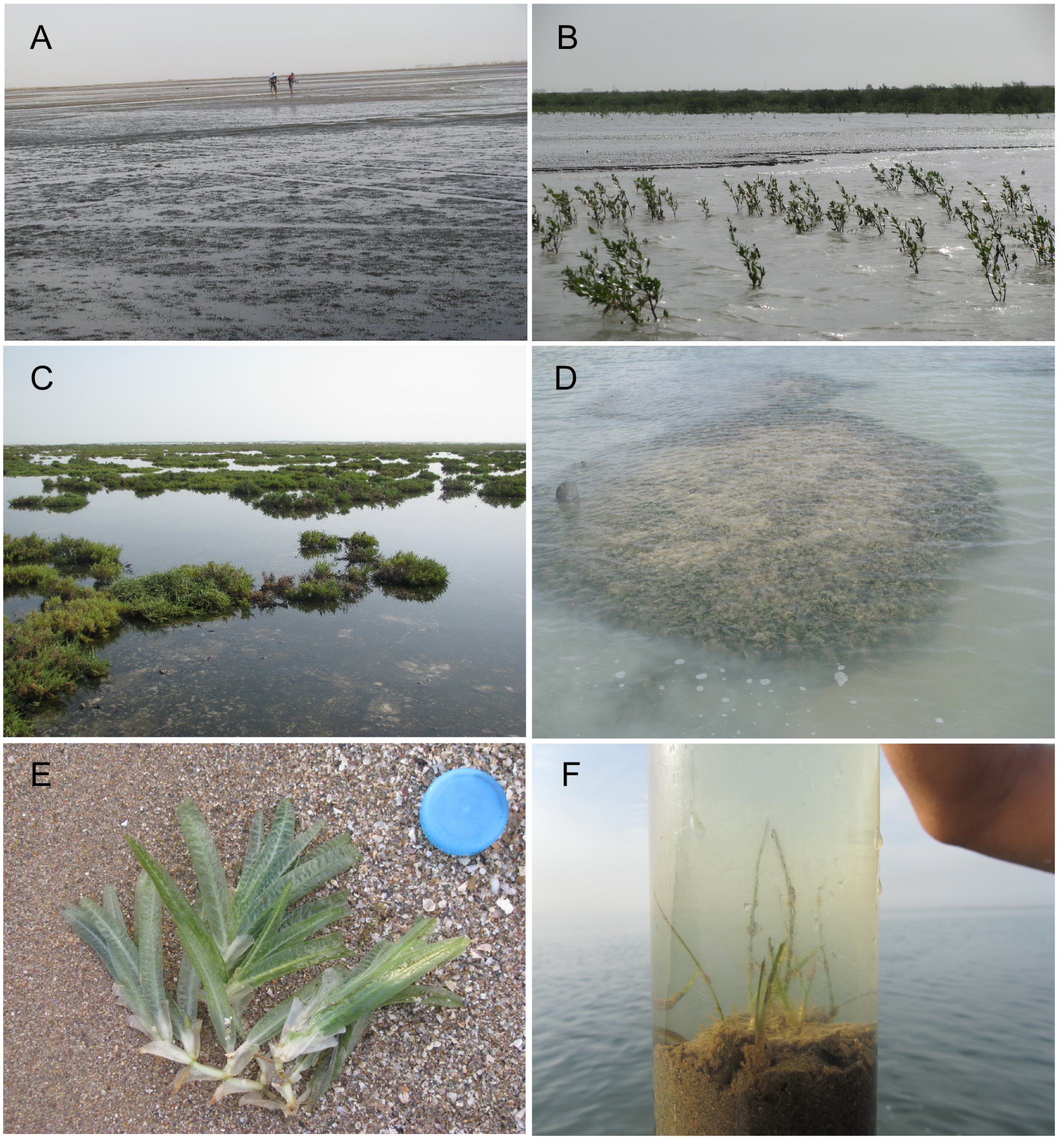

FIGURE 4 | The intertidal sabkha of Al-Kharrar Lagoon during high tide. **(A)** intertidal sabkha. **(B)** the mangroves *Avicennia marina*, **(C)** the coastal shrubs *Salicornia fruticosa*, **(D)** *Avrainvillea* cf. *A. amadelpha*, **(E)** the fan seagrass *Halophila stipulacea*, **(F)** the seagrass *Cymodocea rotundata* (Al-Dubai et al., 2017b).

Zone B is dominated by calcareous species of *P. planatus, C. hemprichii, S. orbiculus, Q. lamarckiana, Q. seminula* and *Q. laevigata* with very low frequencies of agglutinated species. It is distinct from other zones by having the highest percentages of these species recorded on the intertidal sabkha. Zone B extends from 0.5 to 0 m relative to LAT, and mainly contains seagrass *Cymodocea rotundata* (**Figure 6**). Zone **C** is dominated by numerous calcareous species such as *C. hemprichii, Q. costata, S. orbiculus, P. planatus, A. convexa, A. tepida, Spiroloculina communis* and *Spiroloculina costigera.* It differs from other zones by having the highest percentages of deeper water species such as *S. communis* and *S. costigera.* This zone is located between 0 and –0.6 m below the LAT and contains the seagrass *Halophila stipulacea* (**Figure 6**).

Faunal density of dead foraminifers ranged from 2 to about 1000 tests/g with an average value of 165 tests/g, while the dead diversity ranged from 2 to 44 species/sample with an average value of 22 species (**Table 3**). Dead-species diversity decreased asymptotically with increasing intertidal sabkha elevation and decreasing tidal inundation, reaching its lowest value in Zone A (**Figure 6**). The highest abundances of dead foraminifers occurred below MLTW elevation (0.2 m), particularly in Zones B and C, with averages of the most abundant species being *P. planatus* (26%), *C. hemprichii* (10%), *S. orbiculus* (8%), *Elphidium striatopunctatum* (5%), *Q. seminula* (5%), *Varidentella neostriata* (4%) and *A. convexa* 3%). Calcareous species dominated the death assemblages in all intertidal sabkha samples (average 99%); however, agglutinated foraminifers occurred with

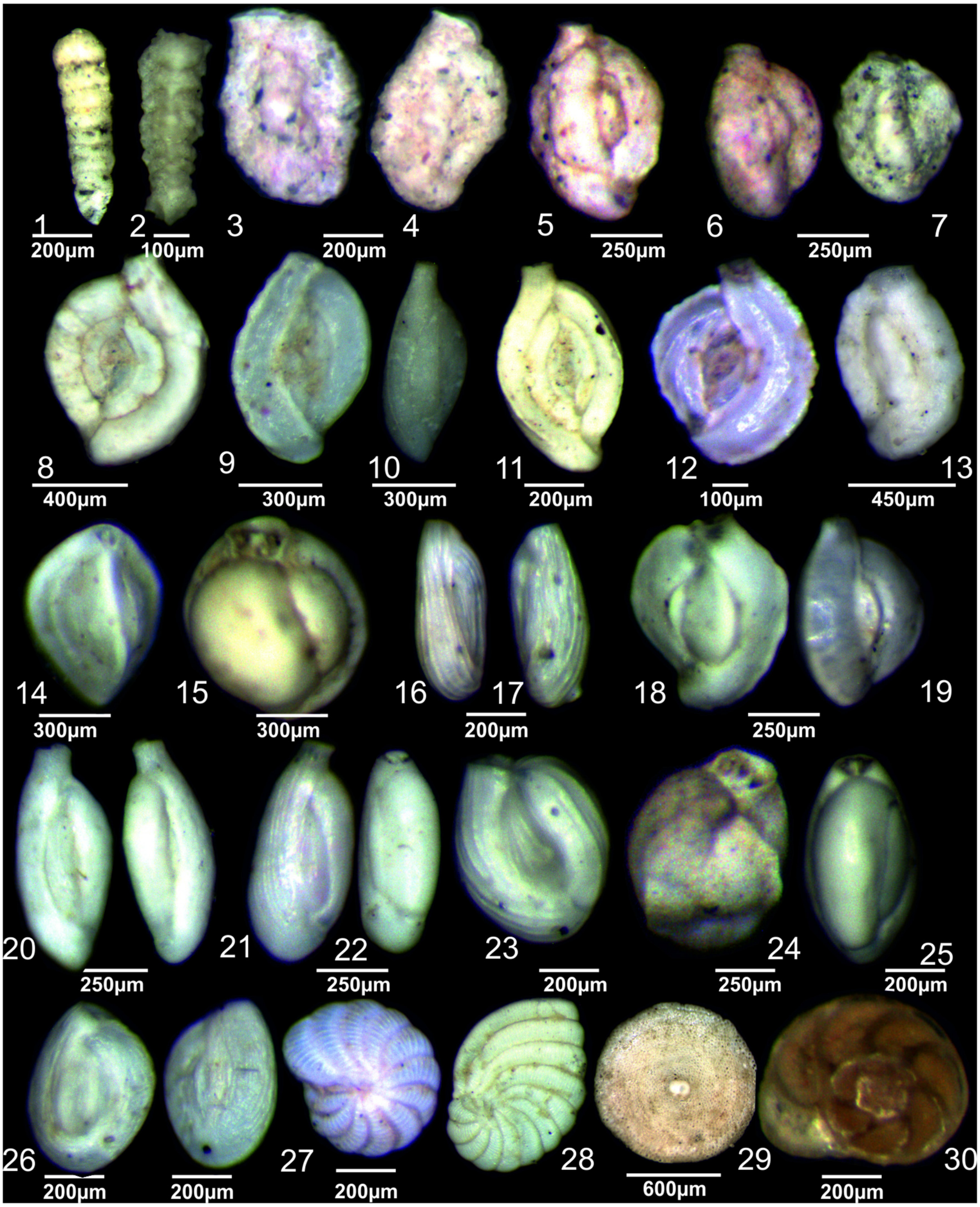

FIGURE 5 | 1 *Clavulina multicamerata,* side view; 2 *Clavulina angularis,* side view, 3–4 *Agglutinella compressa,* side view; 5–6 *Siphonaperta pittensis,* side view; 7 *Siphonaperta* cf. *S. agglutinans,* side view; 8 *S. rugosa,* side view, 9 *Spiroloculina* sp. side view; 10 *Spiroloculina sulcata,* side view; 11 *Spiroloculina communis*, side view; 12 *Spiroloculina costigera,* side view; 13 *Lachlanella subpolygona,* side view; 14 *Triloculina tricarinata*, side views; 15 *Triloculina trigonula*, apertural views; 16–17 *Q. limbata*, side views; 18–19 *Quinqueloculina lamarckiana,* side views; 20 *Cycloforina sulcata*, side view; 21–22 *Cycloforina carinatastriata*, side views; 23 *Triloculina fichteliana*, side views; 24 *Triloculina serrulata*, side view; 25 *Triloculina* cf. *T. schreiberiana*, side view; 26 *Varidentella neostriata,* side views; 27 *Coscinospira hemprichii*, side views; 28 *Peneroplis planatus*, side view**;** 29 *Sorites orbiculus*, side view; 30 *Ammonia convexa*, spiral views.

very low abundance (average 1%), particularly in Zone A and were represented mainly by *C. angularis* (average 0.38%), *A. compressa* (average 0.17%), *C. multicamerata* (average 0.08%) and *Siphonaperta pittensis* (average 0.03%; **Table 3**).

Live Foraminiferal Assemblage

The live species counted in each sample were significantly lower than the dead foraminifers. A total of 68 live species were identified across the intertidal sabkha of KL (**Figure 5**). Only

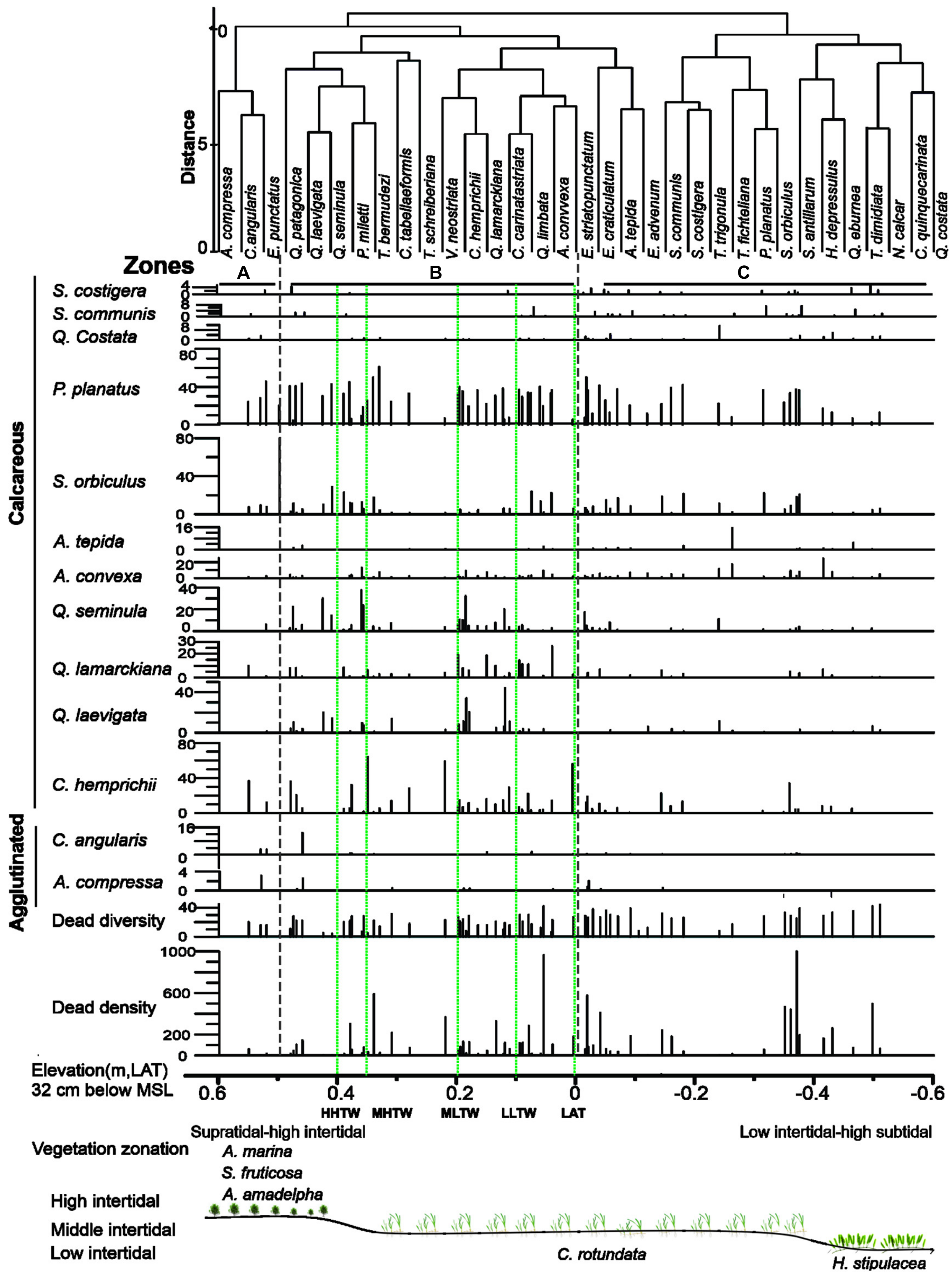

FIGURE 6 | A frequency histogram of the distribution of dead benthic foraminifers across intertidal sabkha vs. the elevation (m, LAT) of the Al-Kharrar Lagoon during March 2014. Cluster analysis of total foraminiferal species based on Log (x + 1) transformed data, and standardized using Bray-Curtis similarity coefficients of group-average. Vegetation zonations based on elevations.

TABLE 3 | Average, density and diversity of the most abundant living/dead foraminifers found on the intertidal sabkha of Al-Kharrar Lagoon.

Living assemblage			Death assemblage		
Calcareous	**Max**	**Average**	**Calcareous**	**Max**	**Average**
A. quadrilateralis	25	2.7	*A. quadrilateralis*	20	2
A. convexa	66.7	5.2	*A. convexa*	24.4	3.21
A. tepida	8.3	0.7	*A. tepida*	15.4	0.50
C. hemprichii	50	5.8	*C. hemprichii*	64.03	10.05
C. carinatastriata	50	2.01	*C. carinatastriata*	9.02	1.3
E. milletti	33.3	0.9	*C. quinquecarinata*	20	0.7
E. striatopunctatum	20	2.1	*E. advenum*	11.1	1.03
M. gualtieriana	21.4	1.5	*E. striatopunctatum*	35.3	4.8
N. calcar	62.1	2	*H. depressulus*	12.5	0.6
P. planatus	70.3	18.8	*M. labiosa*	6.1	0.78
P. subgranulata	25	1.3	*N. calcar*	38.5	1.40
Q. bosciana	42.9	0.7	*P. milletti*	18.3	1.21
Q. costata	12.5	0.9	*P. planatus*	61.1	26.2
Q. laevigata	100	7.3	*P.pertusus*	6.7	0.6
Q. lamarckiana	50	7.8	*Q. costata*	11.1	0.7
Q. limbata	29.3	2.5	*Q. laevigata*	44	3.8
Q. patagonica	20	0.7	*Q. lamarckiana*	26.3	3.2
Q. seminula	100	5.9	*Q. limbata*	20	3.8
R. lepida	25	0.6	*Q. patagonica*	20	0.9
S. orbiculus	63.6	6.6	*Q. seminula*	37.5	4.8
S. antillarum	10	0.6	*S. orbiculus*	80	7.8
S. communis	66.7	1.9	*S. antillarum*	12.5	0.9
S. costigera	25	1.1	*S. communis*	7.2	0.7
T. bermudezi	28.6	1.2	*S. costigera*	4.8	0.5
T. fichteliana	16.1	1.4	*T. bermudezi*	52.4	2.2
T. schreiberiana	32.4	1.9	*T. serrulata*	10	1
T. serrulata	50	1.1	*T. fichteliana*	11.1	0.8
T. trigonula	25	1	*T. trigonula*	6	0.5
T. dimidiata	16.7	0.6	*T. dimidiata*	7	0.4
V. neostriata	33.3	5	*V. neostriata*	26.04	4.3
V. striata	62.5	1.5	*V. striata*	11.8	0.8
Agglutinated	**Max**	**Average**	**Agglutinated**	**Max**	**Average**
A. compressa	5.7	0.1	*A. compressa*	3.13	0.2
C. angularis	7.7	0.3	*C. angularis*	12.8	0.4
C. multicamerata	10	0.3	*C. multicamerata*	1.10	0.1
	–	–	*S. pittensis*	0.6	0.03
Live Density/g	151	17	Dead Density/g	1000	165
Species Diversity (S)	22	8	Species Diversity (S)	44	22

Minimum values are zero in all samples.

5 live agglutinated species were present, and the rest were calcareous (porcelaneous and hyaline) species (**Figure 7**).

Faunal density of the living assemblage ranged from 1 to 150 tests/g with an average value of 17 tests/g, whereas the living diversity ranged from 1 to 22 species/sample with an average value of 8 species (**Table 3**). Species diversity showed a close resemblance to the dead-species diversity, whereby it decreased with increasing intertidal sabkha elevation and decreasing tidal inundation, reaching only one species in the samples in the highest supratidal area (**Figure 7**). The highest abundances of living foraminifers occurred below MLTW elevation (0.2 m), with averages of the most abundant species in the total assemblage being *P. planatus* (18%), *Q. lamarckiana* (8%) *Q. laevigata* (7%), *S. orbiculus* (7%), *Q. seminula* (6%), *C. hemprichii* (6%), *A. convexa* 5%) and *Varidentella neostriata* (5%; **Table 3**). The living assemblage in the whole intertidal sabkha was highly dominated by calcareous foraminifers (average 99%). Whereas, agglutinated foraminifers occurred in Zone A with low abundance (average 1%) and were almost exclusively represented by *C. angularis* (average 0.3%), *C. multicamerata* (average 0.3%) and *A. compressa* (average 0.1%; **Table 3**).

TABLE 4 | Summary statistical parameters of the transfer function of dead foraminiferal training sets using the Weighted Average Partial Least Squares regression (WA-PLS) method for the training data set (N = 75).

Model	**Training data set**		
Method	WA-PLS		
No. of sample	75		
No. of species	111		
Component	**1**	**2**	**3**
RMSE (m)	0.13	0.09	0.06
r^2	0.78	0.90	0.95
Max Bias (m)	0.15	0.07	0.08
$\mathbf{r^2}$ **(jack)**	0.58	0.74	**0.80**
Max Bias (jack, m)	0.30	0.21	0.14
RMSEP (m)	0.18	0.14	0.12

The significant used values RMSEP (jack), r^2 (jack) and components that are highlighted in bold characters.

Elevation and Salinity Relationships of Foraminifers

The distribution of benthic foraminiferal assemblage in the intertidal zone is controlled by dominant factors such as elevation and salinity as indicated in **Figure 6**. Elevation and salinity are directly related to the duration and frequency of tidal inundation in the area. It appears that the optima for most agglutinated species (*Agglutinella compressa, Clavulina angularis* and *Clavulina multicamerata*) occur in the high intertidal zone above HHTW, and decreases toward the lower intertidal zones. Conversely, calcareous species increase toward low intertidal zones, implying that the optimum for most calcareous species is below the HHTW. Therefore, modern benthic foraminifers in the intertidal zones were used to elucidate the relationship between field-observed and model-predicted elevation, which in turn demonstrates the strength and predictive ability of the model. The transfer model was developed from a training set composed of dead benthic foraminifers only; living foraminifers were excluded from this part of the study, since they would be in equilibrium with the environmental conditions prevailing at the time of sampling. This implies that their assemblage changes over time.

A Weighted Averaged Partial Least Squares (WA-PLS) regression model was applied on 75 contemporary sediment samples and 99 species obtained from several transects across the sabkha area accounting for more than 60% of the

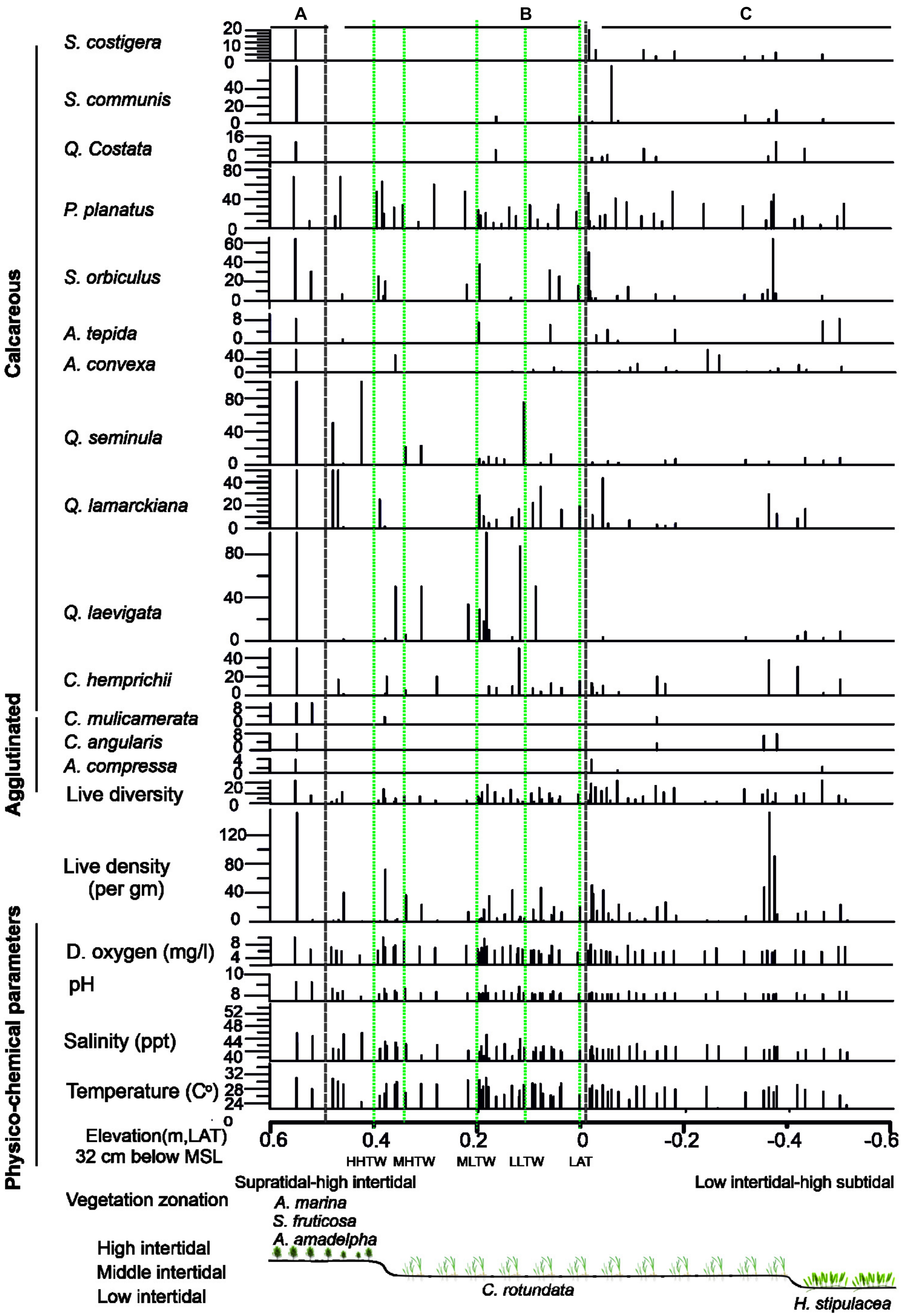

FIGURE 7 | A frequency histogram of the distribution of live benthic foraminifers across intertidal sabkha vs. the elevation (m, LAT) of the Al-Kharrar Lagoon during March 2014. Vegetation zonations based on elevations.

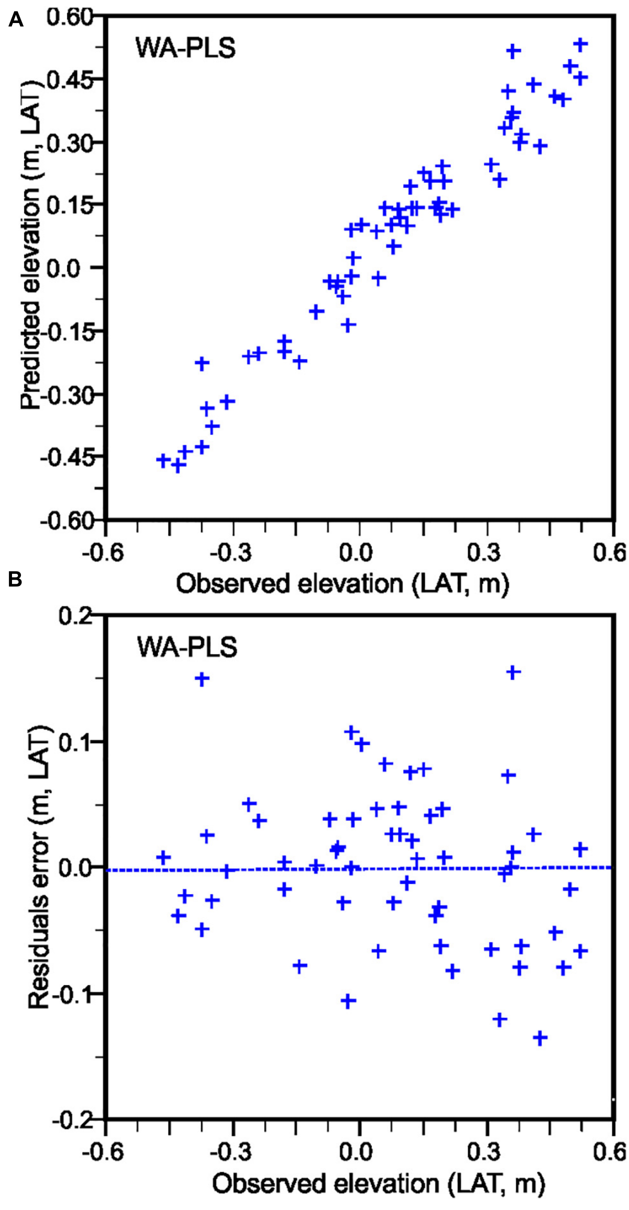

FIGURE 8 | (A) Samples elevations predicted by the WA-PLS regression model, compared with observed elevations. **(B)** Residual errors of WA-PLS is calculated by (subtracting the observed elevations from the inferred elevations) and using the modern training set data (75 samples and 99 species).

total death-assemblage of the KL (**Table 4**). Deeper water samples/species (below –0.5m relative to LAT) were completely omitted from this study since they are always below sea level. The relationship between the observed and foraminiferal-predicted elevation is comparatively strong (r^2_{jack} = 0.80 for component 3). This result indicates that the training set composed of death assemblage counts can predict sabkha reconstruction of palaeotidal elevations in the KL with a precision of ± 0.12m ($RMSEP_{jack}$ = 0.12 m; see **Table 4**). The elevation of samples/species collected from the sabkha ranges between 0.6 and –0.6 (m, LAT) and is shown in the scatter plot of the observed/predicted elevation (m, LAT) with residual errors between 0.2 and –0.15 m (LAT) (**Figure 8**). In **Table 5** we compare our results with some published foraminiferal studies from intertidal/salt marshes intertidal areas of the world.

Canonical Correspondence Analysis

The correlation between the living foraminiferal assemblage and environmental variables of KL was assessed by canonical correspondence analysis (CCA; **Figure 9**). The PCA revealed that ∼89.6% of data variance could be explained by the first three axes (factors). The first axis (eigenvalue = 0.16) explains 41.65% of the variation and is associated with a combination of *T. serrulata* and *H. stipulacea*, the second axis (eigenvalue = 0.12) explains 30.94% of the variation, which is largely explained by *T. serrulata* and *A. amadelpha*, and the third axis (eigenvalue = 0.07) explains 16.99% of the variation, which is largely due to *C. multicamerata* and *T. serrulata* species (**Table 6**). The CCA biplot displays three vertical zonations of sabkha ranging from 0.6 to –0.5 m relative to LAT, characterized by specific species, vegetation cover, and physico-chemical parameters (**Figure 8**). For instance, species *Q. seminula* and *C. multicamerata* occupy the high intertidal, *T. schreiberiana*, *Q. lamarckiana* and *C. hemprichii,* occupy the high and middle intertidal, while *Q. costata, S. costigera, S. communis, A. convexa, A. tepida* and *N. calcar* occur in the low intertidal zone. In the plot of CCA axes (**Figure 9**), elevation is positive correlated with salinity and the foraminiferal species *Q. seminula, S. orbiculus* and *P. planatus*. These species also showed a positive correlation with temperature. *A. convexa, A. tepida*, *N. calcar, S. costigera* and *S. communis* are positively related with dissolved oxygen and pH. In contrast, they are inversely related with elevation. Live density and diversity displayed a positive relationship with dissolved oxygen and pH. However, they showed an inverse relationship with elevation. *P. planatus, C. hemprichii* and *S. orbiculus* are positively related with stressors such as temperature and salinity. *C. rotundata* and *H. stipulacea* are negatively related with the elevation. The high intertidal vegetation (*A. amadelpha, A. marina*, and *S. fruticosa*) zones plot on the left (high elevation, temperature, salinity) and the low intertidal vegetation (*C. rotundata* and *H. stipulacea*) zone plots on the right of CCA (low elevation, pH, dissolved oxygen).

DISCUSSION

Faunal Composition, Distribution and Controlling Factors of Benthic Foraminifers

Al-Kharrar Lagoon is surrounded by extensive intertidal sabkha, extending about 4 km toward the land, which is mainly composed of sand alluvium covered with distinctive coastal vegetation (Al-Dubai et al., 2017a,b). The intertidal bottom sediments are dominated by live benthic foraminiferal species, albeit in low percentages, and they generally increased in abundance with decreasing elevation of the sabkha. Only moderate faunal density

TABLE 5 | Comparisons between our results with modern foraminiferal datasets from other intertidal/salt marshes of the world.

Site	N	Model	$RMSEP_{jack}$ (m)	Mean tidal range (m)	Ref.
Central Red Sea, Al-Kharrar Lagoon	75	WA-PLS	0.12	0.24	The present study
W Red Sea coast, Shuaiba Lagoon	29	WA-PLS	0.16	0.25	Abu-Zied and Bantan, 2013
SW Pacific Tasmania	43	WA-PLS	0.10	0.60	Callard et al., 2011
N Carolina, United States (average of 3 locations)	46	WA-PLS	0.04	0.27	Kemp et al., 2009
NE Pacific Oregon (average of 5 locations)	91	WA-PLS	0.20	1.81	Hawkes et al., 2010
Connecticut, United States (average of 4 locations)	91	WA-PLS	0.18	1.36	Edwards et al., 2004
N Spain (average of 4 locations)	30	WA-PLS	0.19	2.50	Leorri et al., 2008a
Southern Bay of Biscay	46	WA-PLS	0.27	2.5	Leorri et al., 2008b
E Atlantic S England (average of 2 locations)	85	WA-PLS	0.29	3.45	Massey et al., 2006
Galpins salt marsh, South Africa	39	PLS	0.17	–	Strachan et al., 2015

A low value of $RMSEP_{jack}$ means that sea-level changes can be precisely reconstructed from fossil foraminiferal records preserved in sediments. N, number of samples in training set; $RMSEP_{jack}$, Root Mean Square Error of Prediction; WA-PLS, Weighted Average Partial Least Squares.

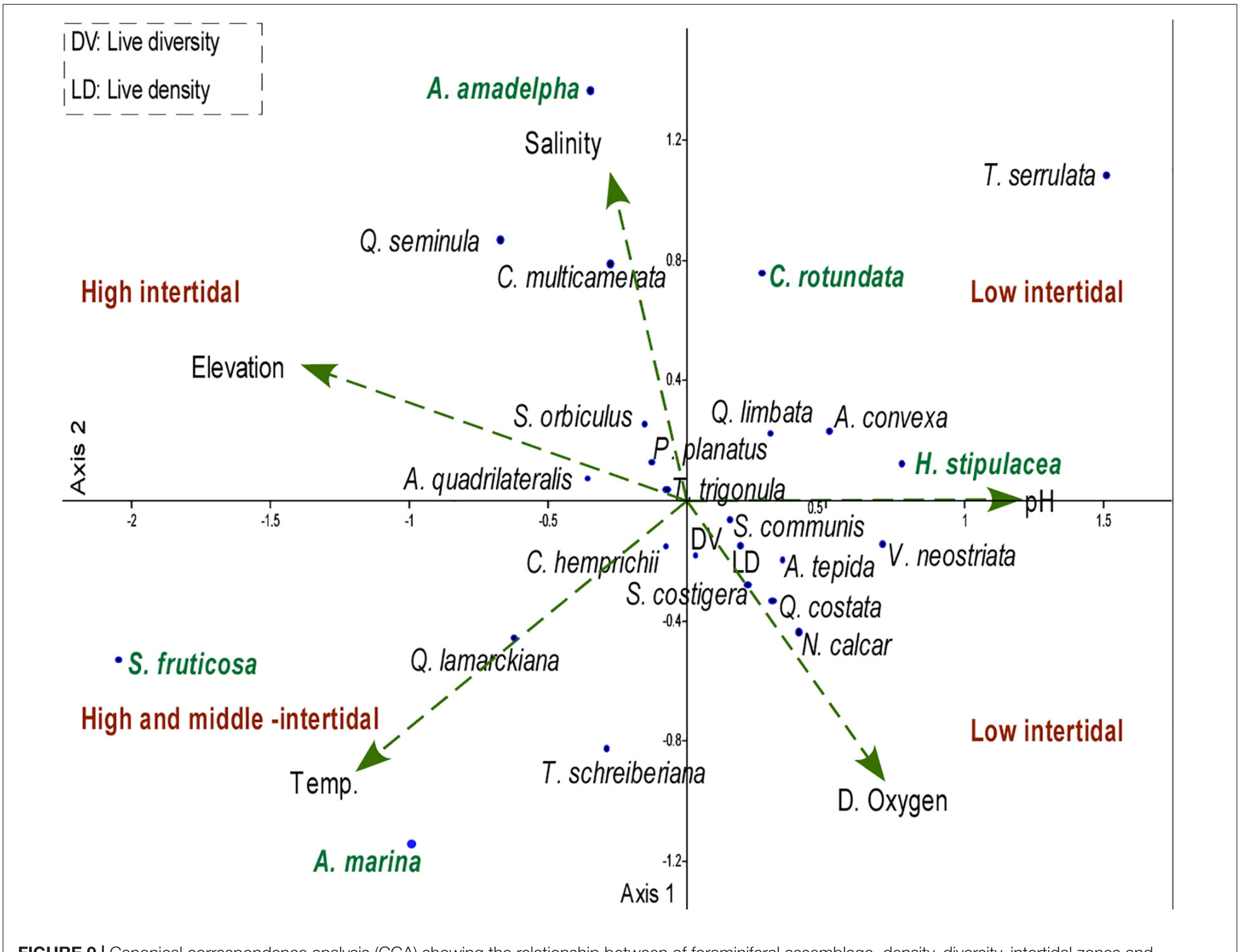

FIGURE 9 | Canonical correspondence analysis (CCA) showing the relationship between of foraminiferal assemblage, density, diversity, intertidal zones and environmental variables (arrows) such as elevation, temperature, salinity, DO, pH in KL.

was recorded in the intertidal zone above 0.2 m elevation at the KL that could be due to the occurrence of frequent stressed conditions accounting for the very low counts of faunal diversity. Salinity and temperature in the study area show a general rising trend from low to high intertidal areas due to the high evaporation and decreasing water cover and depths. Numerous authors (Murray and Alve, 2000; Murray, 2006; Horton and Murray, 2007) reported that the stressful

TABLE 6 | Eigenvalues and cumulative percentage of variances of foraminiferal and environmental data obtained by the canonical correspondence analysis (CCA).

Axis	1	2	3	4	Total inertia
Eigenvalue	0.16	0.12	0.07	0.04	1.8
Variance%	41.65	30.94	16.99	10.42	
Cumulative percentage variance of foraminiferal data	41.65	72.59	89.58	100	

environmental conditions in the intertidal area allow limited species to survive and their reproduction is promoted by their tolerance to the diurnal and seasonal variations in the physiochemical conditions, caused by flood frequency associated with tidal overflow and sea level changes (Eichler, 2019). In contrast, high faunal density accompanied by a relatively high faunal diversity was recorded in the lower intertidal zone below 0.2 m elevation, indicating relatively stable environmental conditions since this elevation is permanently inundated by water and could provide better living conditions. New oxygen-rich water that covers the lower intertidal sabkha during high tide provides good living conditions, which results in a large number of living foraminiferal species (De Rijk and Troelstra, 1999; Berkeley et al., 2007; Scheder et al., 2019). Moreover, the prevalence of coastal vegetation in the lower intertidal area produces oxygen as a result of photosynthesis, which may help promote living foraminifers to reproduce (Al-Dubai et al., 2017a). In addition, many other factors control the abundance and diversity of foraminifers in the intertidal area, including the duration and frequency of intertidal exposure, substrate, temperature, salinity, food (organic matter) and pH (Murray, 1968; Alve and Nagy, 1986; Debenay et al., 2002; Horton and Edwards, 2003; Woodroffe et al., 2005; Abu-Zied and Bantan, 2013). Horton and Edwards (2003) and Eichler (2019) showed that the distribution of surface foraminifers across the intertidal zone of Brazil and the United Kingdom coastlines are controlled by the substrate elevation relative to tidal inundation.

On the other hand, dead foraminifers in intertidal sabkha sediments showed higher faunal density than live foraminifers, indicating a seasonal accumulation of empty tests, or they could be allochthonous and introduced from low intertidal areas by frequent tidal currents (De Rijk and Troelstra, 1999). Murray (1991) and Horton (1999) reported that death assemblages in the intertidal zone are not affected by seasonal variability, and are likely to represent a time-average accumulation for taxa tests. In contrast, live foraminiferal assemblages are in equilibrium with the environment and are affected by seasonal fluctuations and thus vary throughout the year depending on the variation of the environmental conditions. Also, tidal currents are capable of re-suspending foraminiferal tests in the water column, thus causing advective transport of these tests to other places (Eichler, 2019).

Furthermore, the much higher presence of dead than living foraminiferal species could be explained by the good preservation potential of the empty tests without significant dissolution effects.

Most of the dead foraminiferal species in the intertidal zone, especially in the vegetated areas, are not autochthonous in the region, as evidenced by the higher diversity of dead species compared to the living diversity. For example, foraminiferal species *Spiroloculina costigera, S. corrugate, S. rugosa, S. antillarum, S. communis, Triloculina trigonula and T. serrulata* were present in the intertidal area. However, many authors (e.g., Abu-Zied and Bantan, 2015; Al-Dubai et al., 2017a; Bantan et al., 2019) stated that these species represent deeper water (subtidal) species. Therefore, these species represent allochthonous species, probably transported by flood tide currents from the deeper water region. Also, *Bolivina striatula* and *Amphistegina lessonii* were recorded in the intertidal zone, despite their marine habitat. For example, *Amphistegina*, spp. prefer seagrass and hard substrates such as coral rubble (Murray, 2006) at depths of 0 to 50 m (Hohenegger, 2004; Murray, 2006), while *Bolivina striatula* prefers coastal marine environments with normal marine salinity (Eichler, 2019). *Cibicides lobatula* was not present in the intertidal sabkha in either the life or death assemblages, but was reported below LAT (–0.36 m, subtidal) in the KL. Therefore, species that did not occur in the intertidal zone in both life and death assemblages, are probably not autochthonous in this zone and may represent species typical of deeper marine environments that were transported postmortem by tidal currents. In Basque marshes (Spain), especially at mid-tidal elevations, *C. lobatula* has a distinct presence and was considered as an allochthonous species (Leorri et al., 2010). The same results have also been found on the coasts of Britain (Horton and Edwards, 2006; Massey et al., 2006). Thus, our results corroborate works done by Horton and Edwards (2006), Massey et al. (2006), Leorri et al. (2010). On the other hand, some live species have been recorded along the intertidal sabkha around KL (e.g., *Coscinospira hemprichii, Peneroplis planatu, Quinqueloculina laevigata, Q. lamarckiana, Q. seminula, Triloculina fichteliana, T. schreiberiana, Sorites orbiculus, Varidentella neostriata* and *Ammonia convexa*), suggesting that these species are probably autochthonous species in the area. These calcareous (hyaline and porcelaneous) species compose 99% of the total assemblage. In accordance with our expectations, a taphonomic loss of calcareous species could increase due to dissolution in low-pH sediments associated with early diagenesis of organic carbon and the release of CO_2, as occurs in many intertidal/salt marshes areas of the world (Scott and Medioli, 1980b; Murray and Alve, 1999; Gómez-León et al., 2018; Eichler, 2019). However, this is not the case in the intertidal sabkha analyzed here, as the calcareous shells are well preserved and do not seem to be affected by dissolution, probably due to the high pH (∼9) values of most Al-Kharrar intertidal regions since these waters are supersaturated with respect to $CaCO_3$ resulting from a high input from surrounding older limestone rocks, which reduces the solubility of the calcareous shells. Photosynthesis consumes CO_2 and produces alkalinity, creating precipitation conditions for carbonate, while respiration process causes calcium carbonate dissolution (Moreno et al., 2007). Al-Dubai et al. (2017b) reported that the alkaline (pH ∼9) water in the intertidal zone of KL can be attributed to the consumption of CO_2 and production of O_2 during photosynthesis by the algal mats covering the intertidal area, or due to degassing of CO_2 as a result of rising temperature (>33°C). Hence, the dissolution of calcium carbonate decreases with increasing temperature (Bai and Bai, 2019). In many regions of the world (e.g., Basque marshes, Spain), calcareous species in the total assemblage (living plus dead) constitute an important component in the marshes (Leorri et al., 2010). They concluded that the dissolution of calcareous tests was less prolific, due to the marshes being supplied with carbonate materials ($CaCO_3$) from the surrounding regional limestone rocks (Cearreta and Murray, 2000). This could make the ambient water saturated with calcium carbonate, thereby reducing the solubility of carbonate tests and increasing the calcification rate in the area (Langdon et al., 2000) and thus enhancing the shell preservation potential. On the other hand, agglutinated species (e.g., *Agglutinella compressa, Clavulina angularis* and *C. multicamerata)* were found in the intertidal sabkha, but in low percentages (about ∼1%). These species are probably autochthonous species in the intertidal sabkha because they are present in both the living and death assemblages. The intertidal sabkha of KL is characterized by low-energy environments with muddy sand substrates rich in mangrove and coastal vegetation. It also has a salinity of up to ∼44 ‰ and temperature of ∼33°C. Thus it is a sheltered environment that is relatively more suitable for agglutinated species than those subtidal areas that are open to the sea. In the latter areas (unprotected areas), agglutinated tests are subject to abrasion, breakage and transportation due to currents and wave activity, and thus their tests are disintegrated immediately after their death (Murray, 2000; Abu-Zied et al., 2011). On the contrary, a mangrove environment is the preferred site for agglutinated species because mangrove roots create a calm environment that effectively dissipate waves and currents (Berkeley et al., 2007; Hewaidy et al., 2019). Abu-Zied et al. (2011) reported that *C. angularis* were frequent in the intertidal zone of Khor As Sailah on the Farasan Islands in southern Saudi Arabia but were absent in other parts of the same island. They attributed this to the low-energy conditions at Khor As Sailah that was colonized with mangroves, thus enhancing their preservation potential. However, the low abundance of agglutinated species in Al-Kharrar Lagoon could be well explained by the prevalence of sand substrates, which may preclude agglutinated species, since they generally prefer muddy substrates (Jones and Charnock, 1985; Hohenegger et al., 1993; Haunold et al., 1997; Berkeley et al., 2007; Abu-Zied et al., 2011). Reiss and Hottinger (1984) mentioned that agglutinated species also inhabit warm hypersaline lagoons at water depths of 0–1.5 m. However, these findings are inconsistent with what has already been reported by several authors (Scott and Medioli, 1980a; Sen Gupta, 1999; Kemp et al., 2009; Farouk and Jain, 2018). Eichler (2019) documented that agglutinated species were found in mixohaline and brackish environments in the Bertioga Channel (São Paulo, Brazil) and that their number decreased toward more saline environments.

The distribution of both benthic foraminifers and vegetation in intertidal sabkhas is related to tidal inundation, thus, the foraminiferal assemblage in surface sediments could be used as an indicator of tidal inundation and also intertidal surface elevation relative to msl (Horton and Edwards, 2006; Rogers et al., 2017). Several authors (Horton et al., 1999; Edwards and Horton, 2000; Gehrels, 2000; Edwards et al., 2004; Horton and Edwards, 2006) demonstrated that studies of the distributions of saltmarsh/intertidal foraminifers led to a significant development of the TF used to infer the past elevations of fossil saltmarsh/intertidal deposits. Local transfer functions are therefore needed to reconstruct palaeotidal surface elevations and, thereby, past sea level in the intertidal sabkha in Al-Kharrar lagoon and similar adjacent regions.

Evaluation of the Transfer Function

The contemporary foraminiferal assemblage exhibited three spatial zonations along the intertidal sabkha based on cluster analysis, indicating that it is highly influenced by elevation in the tidal frame, which is consistent with other studies (Horton and Edwards, 2003; Woodroffe et al., 2005; Callard et al., 2011; Strachan et al., 2015). The agglutinated species (*Agglutinella compressa, Clavulina angularis,* and *Clavulina multicamerata*) dominate the high intertidal zone, and decrease toward the low intertidal zone, indicating that this assemblage is restricted to a 0.4 m vertical range above HHTW. On the contrary, calcareous species increase toward lower intertidal zones and decrease toward the high intertidal zone, indicating that the optima level is below 0.40 m HHTW. Several other studies also documented that agglutinated species dominated in the high-middle marshes (Strachan et al., 2015; Lal et al., 2020), while calcareous species dominated lower intertidal and subtidal environments (Hayward et al., 1999, 2015).

A transfer function model was developed based on a screened data set comprising 75 contemporary sediment samples and 99 benthic foraminiferal species obtained from the supratidal-high subtidal areas of KL, where elevation ranged from 0.6 to –0.5 m (LAT), since these samples/species showed a good correlation with the tidal elevation. However, the subtidal and deeper water samples/species (below –0.5 m relative to LAT) were omitted to obtain a more accurate training dataset model for the KL. Many authors (e.g., Jones and Juggins, 1995; Edwards and Horton, 2000; Edwards et al., 2004; Hamilton and Shennan, 2005; Woodroffe et al., 2005; Massey et al., 2006; Horton and Murray, 2007) concluded that the incorporation of subtidal and deeper water samples/species with the intertidal agglutinated benthic foraminifers in the model may reduce the predictive ability of the transfer function and, hence, may provide an inaccurate predictor for sea-level elevations. This is because the subtidal and deeper water samples/species displayed no relationship with tidal elevation (Abu-Zied and Bantan, 2013). The precision of the transfer function of model Weighted Averaged Partial Least Squares (WA-PLS) was comparatively strong with the relationship between the observed and predicted elevations in the model being high (r^2_{jack} = 0.80 for component 3). Regression modeling of the modern training set indicates intertidal foraminiferal assemblages can predict intertidal surface elevations in the Al-Kharrar Lagoon with a precision of ±0.12 m ($RMSEP_{Jack}$ = 0.12 m). Therefore, the WA-PLS regression model is suitable to be used to reconstruct palaeotidal elevations since the estimated predictive measure resulting from the training set was less than the daily tidal range of 0.24 m in Al-Kharrar Lagoon. The results for our study area was comparable with other results of foraminiferal-based transfer functions from other sites in the world. However, at those sites around the world with small tidal ranges (e.g., Tasmania in the southwestern Pacific, and North Carolina) the results were more precise than our result, reaching ± 0.05 m (e.g., Gehrels et al., 2005; Southall et al., 2006; Kemp et al., 2009). A similar study was conducted in South Africa, where benthic foraminifers were used to determine the vertical distribution of the foraminifers and to test its potential for use in studies of sea-level changes (Strachan et al., 2015). The transfer function was applied to benthic foraminifers from Galpins salt-marsh and this study revealed that salt-marsh foraminifers can predict marsh surface elevations with a precision of ±0.17 m. Locally, the present result was slightly more precise than those recorded by Abu-Zied and Bantan (2013) in the intertidal zone of the Shuaiba Lagoon (80 km south Jeddah City, ±0.16 m). Benthic foraminifera from intertidal sabkha on the Saudi Red Sea coast has demonstrated its ability to assess former changes in sea-level, and therefore should be used as an effective tool in reconstruction studies of relative sea-level changes in the region, similar to those published in other regions of the world.

CONCLUSION

Foraminiferal assemblages obtained from surface sediments along the intertidal sabkha of Al-Kharrar Lagoon show a clear vertical zonation in the study area. Three major intertidal zones (A, B, and C) were identified based on cluster analysis and dominance of particular species. Zone A was found in the high intertidal zone typically above HHTW and is dominated by *A. compressa, C. angularis* and *C. multicamerata*. Zone B was common in middle intertidal area and is dominated by *P. planatus, C. hemprichii, S. orbiculus, Q. lamarckiana, Q. seminula* and *Q. laevigata*. Zone C was found in low intertidal areas and is dominated by *C. hemprichii, Q. costata, S. orbiculus, P. planatus, A. convexa, A. tepida, S. communis,* and *S. costigera*. Factors controlling the vertical distribution of foraminiferal assemblages in the intertidal sabkha are the intertidal elevation and salinity, which are related to the duration and frequency of inundation associated with the tides. Agglutinated species predominantly occurred at higher intertidal elevations where high salinity occurs, whereas calcareous species dominated at lower intertidal elevations and increased in abundance toward lower intertidal zones. The calcareous shells in the intertidal sabkha are well preserved and do not seem to be affected by dissolution due to the waters being oversaturated with respect to calcium carbonate ($CaCO_3$) resulting from the high input from the surrounding older limestone rocks. Dissolution is also inhibited due to the alkaline conditions (∼ pH 9) in the lagoon that reduced the solubility of the shells. The relationship between foraminiferal assemblages and environmental variables (e.g., elevation and salinity) for the intertidal sabkha around Al-Kharrar Lagoon provides greater confidence that these data could be used as a modern analog to assess the past sea-level with high accuracy. The differences between zones suggest that a transfer function is required to obtain a more accurate prediction of sea-level changes.

We developed a transfer function model from a dataset consisting of 75 samples and 99 foraminiferal species using WA-PLS regression. Regression modeling of the modern training set indicates foraminifers can assess sea-level changes with a precision of 0.12 m. We concluded that the modern training set in the sabkha provides great potential to reconstruct past sea level, and thus future assessment of those changes in the area.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: This study uses all publicly available data: Saudi Aramco Tide Tables, 2014 are available (at https://doi.org/10.6084/m9.figshare.15130386.v1). All data used to produce these results can be found (at https://doi.org/10.6084/m9.figshare.15130383.v1) and all figures and tables are available (at https://doi.org/10.6084/m9.figshare.15130296.v1). The software used in this study are free and they are: C2 software version 1.7.7 is available upon registration (at https://www.staff.ncl.ac.uk/stephen.juggins/software/C2Home.htm), while PAST software version 4.03 is available upon registration (at https://past.en.lo4d.com/windows).

AUTHOR CONTRIBUTIONS

TA-D collected the field samples, performed the methodology, carried out the data analysis, prepared the figures and tables, and wrote the original draft. RB did the conceptualization, supervised the data, and carried out the funding acquisition. RA-Z did the conceptualization, supervised the data, collected the field samples, performed the methodology, and reviewed the manuscript. AA-Z collected the field samples and performed the methodology. BJ reviewed and commented on all the drafts. All authors contributed to the article and approved the submitted version.

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