Deciphering Depositional Environment of Playa Lakes Using Grain Size Parameters in the Arid and Semi-Arid Region of Rajasthan, India

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Abstract: This study encompasses the grain size distribution of the playa lakes (Pachpadra, Pokhran, and Didwana) of the Thar Desert in Rajasthan, India. The grain size of sediment particles is the most fundamental feature, giving essential information regarding their origin, transport history, and depositional conditions. The aeolian and fluvial transport processes were evaluated through environmentally sensitive grain size subpopulations to identify the differential sedimentary sources and dynamics in the playas. End-member modelling further determined the sediment grain size distribution through statistical analysis. The playa sediments mainly consist of very fine sand (46–54\%) and very coarse silt (22–37\%). The results show that the average fine fraction of Pachpadra, Pokhran, and Didwana playa was 46.29%, 66.11%, and 66.28%, respectively. In contrast, the average coarser fraction deposition in Pachpadra, Pokhran, and Didwana corresponds to 53.71%, 33.89%, and 33.72%, respectively. This suggests that the playas mostly contain aeolian sediment rather than fluvial sediment transported by dust/sand storms. Additionally, the textural pattern and depositional distribution of the sediments determined through the Passega CM diagram and bivariate plots indicate that 82% of the samples were poorly sorted, and 18% were very poorly sorted. Furthermore, an environmentally sensitive grain size component (ESGSC) was also assessed to identify the spatial variability and transport processes of sediment between these playas. Three ESGSCs in Pokhran (250 µ, 31 µ, and 2 µ) and Pachpadra (125 µ, 31 µ, and 4 µ), while two ESGSCs in Didwana playa (125 µ and 16 µ) were identified, indicating sediment deposition with moderate velocity in a low energy environment with a mixed sediment population transported by aeolian and fluvial activities.

Keywords: playa lakes; depositional environment; end-member modelling; environmentally sensitive grain size; sediment; arid

1. Introduction

Playas have a dynamic ecosystem with multifaceted features of complex geochemistry, biology, and hydrology. These enclosed bodies of water are formed mainly in arid and semi-arid regions where drainage basins are closed [1,2]. Playas are primarily characterized by high salinity, alkaline brines, and a centripetal drainage pattern with no outflow that disappeared when evaporation processes exceeded recharge, making them reactive to climate change and any environmental fluctuations having geochemical impacts on these playas. Despite their ephemeral nature, these are essential to communities, ranchers, rural agricultural economies, and a diverse range of wildlife. Thus, playas are a potential research area to record environmental changes, depositional environment, and geomorphic evolution.
The grain size of sediment particles is the most fundamental feature, influencing their entrainment, transport, and deposition. Grain size analysis gives crucial information regarding sediment origin, transport history, and depositional conditions. In desert ecosystems, a playa lake’s sediment can be helpful in comprehending the sedimentary processes for different climatic conditions over a geological timescale. These sediments are composed of inorganic and organic materials and are classified as allogenic, endogenic, or authigenic based on their mode of genesis [3]. During the pre-monsoon (April-June) season, northwest (NW) India is subjected to frequent and violent dust storms due to arid weather and strong winds, supplying aeolian sediment. However, the monsoon (June-September) season carries fluvial sediment to playas, which produces reworked sediment with multiple peaks [4,5]. Multiple peaks in sediment grain size distribution (GSD) indicate different transport mechanisms and sedimentation processes [6,7]. Therefore, unmixing the GSD would help to determine the origin, transport, and deposition of sediment in playa lakes [8–12]. Multivariate statistical methods, factor analysis, and discriminant analysis were used to characterize the mechanisms of transport, deposition, and the differential sedimentary environment of the GSD [13–21]. Bivariate plots of the discriminant functions based on grain size parameters are also used to classify sediments of unknown origin and decipher the depositional processes in different environmental settings such as desert, coastal, and lacustrine ecosystem using grain size parameters [12,15–18,22,23]. Several researchers proposed unmixing algorithms to differentiate the depositional processes and source environments using grain size data from sediment [9–11,23–27].

Grain-size end-member modelling is an alternative to conventional approaches that can aid in unmixing compositional grain-size data of sediments, e.g., the EMMA algorithm based on a simplex expansion [28], the EMMAgeo algorithm based on principal component analysis [29,30], AnalySize [31], and BEMMA [32]. The extreme environmental conditions and the depositional setting make them an important sink for different depositional processes. However, we found an existing research gap in analyzing the depositional environment of the playa lakes in the Indian region. Hence, an attempt has been made to explore the depositional process and hydrodynamic conditions of playas in the Great Indian Thar Desert. In this study, we applied an end-member modelling algorithm that Paterson and Heslop (2015) proposed to separate the distributions of sediment grain sizes [31]. The objectives of the study were to evaluate the aeolian and fluvial transport processes in the playa lakes using an end-member modelling algorithm; to identify the environmentally sensitive grain-size subpopulations, which further aims to discuss their implications on the differential sedimentary sources and dynamics between the eastern and western playas (Pachpadra, Pokhran, and Didwana playa) across the Thar Desert of Rajasthan.

2. Materials and Methods

2.1. Regional Setting

The Thar Desert, also known as the Great Indian Sand Desert, is located between the states of Rajasthan and Gujarat in India and Sindh in Pakistan and spreads across an area of 250,000 km² [33]. It is the most heavily populated desert area in the world, and the main occupations of the people living here are agriculture and animal husbandry. The Aravalli Mountains range confines the Thar Desert in the east. It physiographically divides Rajasthan into the eastern part (semi-humid) and the western part (semi-arid to arid). It supplies clastic materials (e.g., quartz, mica, feldspar, plagioclase, kaolinite, illite-smectite, etc.) to the adjacent streams. The Thar Desert consists of xeric and sparse vegetation, and the dominant species are Prosopis cineraria, Acacia arabica, Acacia nilotica, Acacia Senegal, Abutilon indicum, and Aerva tomentasa. The average annual rainfall is less than 500 mm on the eastern border and 100 mm on the western border. The temperature during the summer surges to 50 °C, and in the winter, it falls below 6 °C. The evapotranspiration rate is higher than the precipitation rate, meaning that this area has a negative water budget [34].
Several ephemeral playa lakes with salt-encrusted surfaces are found in the region, which get flooded during the monsoon. The major playas of this region are Sambhar Lake, Pachpadra, Didwana, Sujangarh, Lunarkansar, Pokhran, Chhapar, and Jamar. The area enclosing the eastern and western sides of the playa exposed to the dunes, and the clastic received in the playa region was contributed by the eastern Aravalli mountains [35]. Excessive sediment deposition at river confluences, dune segments of streams at late paleoclimatic transitions [36–38], and the formation of rift and horst structures due to tectonic movements along contours point to the playas tectonic-geomorphic evolution [39]. These playas are mainly recharged by surface runoff from the southwest (SW) monsoon, deriving sediments from the chemical weathering of rocks in the Aravalli mountains [35,40]. Moreover, a higher evapotranspiration rate in the region results in the hyper-salinity of the playas [41,42].

Three playas, namely, Pokhran, Pachpadra, and Didwana, were selected based on the rainfall pattern of the study area and its association with the ephemeral stream network (Figure 1). The Pachpadra playa lies in the Barmer district, 60 miles SW of Jodhpur city, occupying an area of approximately 10 km$^2$ and receiving 300 mm of annual rainfall. The Pachpadra playa was formed by the disorganization of the old Luni River [34]. Pachpadra is surrounded by aeolian dunes and is dominated by minerals like halite and calcite, with a low gypsum content. The oval-shaped Didwana is the second-largest playa (13.5 km$^2$) in western Rajasthan, located at the edge of the Thar desert. This playa is chemically enriched with halite minerals and nourished by the monsoon rainfall. The Pokhran playa (12 km$^2$) is situated in the south-eastern (SE) part of the Jaisalmer city of Rajasthan, which receives 200 mm of annual rainfall. The mineral composition of Pokhran playa is mainly comprised of halite with trace levels of dolomite and gypsum [34]. All the playas are surrounded by sparse vegetation and agricultural land (Figure 1). There is no big river that feeds these playas. Most of their water comes from rain during the monsoon season. However, they are dry during the summer.

![Figure 1](image-url). Location map of the study area and the morphological features around the Playas (a) Thar Desert, (b) Didwana Playa, (c) Pachpadra Playa, and (d) Pokhran Playa. The map was created in ArcGIS v10.6, and LULC-2019 data were downloaded from ESRI [43].
2.2. Methodology

2.2.1. Sampling Plan and Sample Collection

The background data for the study was collected through well-planned sampling based on literature, satellite image interpretation, and a site survey. Several approaches were reviewed for sampling, and systematic gridded sampling was adopted in the study. The $1 \times 1$ km grids were drawn on Pokhran and Didwana playa, while $0.3 \times 0.3$ km grids were drawn on Pachpadra playa, and 17 grid cells covered Pokhran, Pachpadra, and Didwana playa to represent an equal number of samples. We sampled one surface sediment from each grid cell in Pokhran, Pachpadra, and Didwana playas at 0–15 cm depth after removing the upper layer of salt crust. Fifty-one samples were collected in Ziplock bags, labelled, and stored in an ice chest at 4 °C. The surface sediments contained a mixture of grain size particles reflecting the sediment’s different origins.

2.2.2. Sample Preparation and Grain Size Estimation

Sediment samples were air-dried to remove moisture and later treated with hydrogen peroxide (30%) and hydrochloric acid (10% v/v) to eliminate organic matter (OM) and inorganic carbon (iC), respectively. Biogenic silica content, a considerable component of the diatomaceous valves, influences the GSD of the sediments. Hence, to remove biogenic silica content, the samples were treated with an alkali solution (10% KOH) in a water bath at 80 °C, followed by washing with distilled water, and lastly centrifuged at a speed of 3500 rpm for 10 min and dispersed with $(\text{NaPO}_3)_6$ by ultrasonication for 15 min. After discarding the supernatant, the pellet was dried and stored in a plastic vial, as explained by Vaasma [44] and Wang [11]. One gram of the sample was weighed and analyzed using a laser particle size analyzer (LPSA). The samples were subjected to a Microtrac S3500 laser diffraction particle size analyzer (Microtrac Inc., Largo, FL, USA) to determine the grain size within the range of 0.02–2000 µm. It measures the particle size distribution by the volume standard.

2.2.3. Statistical and Geospatial Analysis

The grain size distribution and sample statistics were computed based on the method explained by Folk and Ward [45,46], which uses the following relations (Equation (1) to (4)) for the computation of mean ($M_z$), mode, sorting ($\sigma_I$), skewness ($Sk_I$), and kurtosis ($K_G$), and the description is given in Table 1. Several other authors also used a similar relationship [47–49] to calculate the mean, mode, sorting, skewness, and kurtosis.

\[
\text{Mean (}M_z\text{)} = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3} \quad (1)
\]

\[
\text{Sorting (}\sigma_I\text{)} = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_{5}}{6.6} \quad (2)
\]

\[
\text{Skewness (}Sk_I\text{)} = \frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_{5} + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_{5})} \quad (3)
\]

\[
\text{Kurtosis (}K_G\text{)} = \frac{\phi_{95} - \phi_{5}}{2.44(\phi_{75} - \phi_{25})} \quad (4)
\]

where $\phi_5$, $\phi_{16}$, $\phi_{25}$, $\phi_{50}$, $\phi_{75}$, $\phi_{84}$, and $\phi_{95}$ represent the 5th, 16th, 25th, 50th, 75th, 84th, and 95th percentiles, respectively, on the cumulative curve.

The inverse distance weighting (IDW) method is a deterministic spatial interpolation model that is widely used by geoscientists. This technique computes the values of nearby weighed locations to calculate the average value of unsampled locations. The interpolated value is close to the nearest measured value [50]. So, the surface sediment results were plotted using the IDW interpolation technique using the ArcGIS spatial analyst extension.
Table 1. Grain size parameters and grading standards adopted from Folk and Ward (1957) [45].

<table>
<thead>
<tr>
<th>Sorting (σI)</th>
<th>Skewness (SkI)</th>
<th>Kurtosis (KGI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.35 Very well sorted</td>
<td>−0.3—1.0 Very coarse skewed</td>
<td>&lt;0.67 Very Platykurtic</td>
</tr>
<tr>
<td>0.35–0.50 Well sorted</td>
<td>−0.1—0.3 Coarse skewed</td>
<td>0.67–0.90 Platykurtic</td>
</tr>
<tr>
<td>0.50–1.00 Moderately sorted</td>
<td>+0.1—0.1 Symmetrical</td>
<td>0.9–1.11 Mesokurtic</td>
</tr>
<tr>
<td>1.00–2.00 Poorly sorted</td>
<td>+0.1–0.3 Fine skewed</td>
<td>1.11–1.50 Leptokurtic</td>
</tr>
<tr>
<td>2.00–4.00 Very poorly sorted</td>
<td>+0.3–1.0 Very fine skewed</td>
<td>1.50–3.00 Very Leptokurtic</td>
</tr>
<tr>
<td>&gt;4.00 Extremely poorly sorted</td>
<td>&gt;3.00 Extremely</td>
<td></td>
</tr>
</tbody>
</table>

2.2.4. End-Member Modelling

End-members (EMs) are closely related to non-negative compositional data that provide relative information. A specific sample’s compositional variance can be attributed to a mixture of a fixed number of compositions indicated as end-members. EM modelling has been widely used to deduce quantitative and geo-scientifically significant end-members from the original data set. It is a mathematical method for “unmixing” sedimentary processes or sources in different depositional environments.

Paterson and Heslop (2015) proposed a new parameterized grain size EM analysis method [31] based on the generalized Weibull function. It converts the original distribution into a unimodal EM. The optimal number of EMs is determined using the coefficient of determination (R²) and the angular deviation (θ) between the EMs and the GSDs. This technique gives accurate fitting results and helps to avoid data overfitting [51]. In AnalySize, the unmixing of sediment’s GSDs begins with a nonparametric EM analysis procedure to estimate the number of subpopulations potentially contributing to the sediment GSDs and their initial parameters. This design aims to take advantage of the genetic information in a group of GSDs to produce unimodal end-members. The General Weibull Distribution function (Equation (5)) used for parameterization [52,53] has a general form as follows:

\[ f(x, \alpha, \beta) = \frac{\alpha}{\beta^n} x^{n-1} e^{-\left(\frac{x}{\beta}\right)^n} \]  

where \(x, \alpha, \text{ and } \beta\) are independent variables, shape, and scale parameters, respectively. \(\alpha\) determines the breadth of the distribution, while \(\beta\) controls the modal value of the distribution.

In this study, the distribution of EMs from Pachpadra, Pokhran, and Didwana playa was calculated using the AnalySize software package [31], which provides a comprehensive set of tools for analyzing GSD data. It can process a wide range of datasets obtained from laser diffraction particle size analyzers. AnalySize was downloaded from https://www.github.com/greigpaterson/AnalySize (accessed on 1 June 2022) and run using MATLAB version R2015a [54].

2.2.5. Sediment Transport and Deposition

The CM diagram is a method used to describe sediment transport and depositional processes, where the first percentile (C) values are plotted against the median (M) values [55,56]. According to Passega (1964, 1957, and 1969), the first percentile refers to the particle size, representing the maximum capacity of the transport medium [56,57].

2.2.6. Environmental Sensitive Grain Size Component

The Environmentally sensitive grainsize components were determined using Equation (6) [58] for each grain size class given by the Microtrac S3500 laser diffraction particle size analyzer.

\[ S_i = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1}} \]  

(6)
where \( S_i \) is the standard deviation for the grain size class \('i'\), \( x_i \) is the frequency of the grain size of class \('i'\) in the grain size distribution curve, \( X_i \) is the average value of the grain size of class \('i'\), and \( n \) is the number of samples.

3. Results and Discussion

3.1. Grain size Distribution and Nature of Sediments

Grain size distribution, textural forms, and depositional patterns in a lake environment indicate the variation in transportation kinetic energy. A descriptive statistic was applied to the GSD pattern of Pachpadra, Pokhran, and Didwana playas. The mean, standard deviation, skewness, and kurtosis of the three playas are given in Table 2, which suggests that Pokhran and Didwana playas have very coarse silt sediment while Pachpadra playa has very fine sand deposition. Sediments in all three playas are poorly sorted, finely skewed in the case of Pokhran and Didwana, and very finely skewed in the case of the Pachpadra playa, deposited under a uniform energy environment. Figure 2 depicts the spatial distribution of mean grain size (Mz), which reveals that smaller particles are deposited near the center of the Pokhran and Didwana playas. At the same time, in the Pachpadra playa, they were deposited in the eastern and western parts because the playa’s central part is slightly elevated than the adjacent part. Most of the larger particles are deposited near the edges of these playas. The soil texture showed that out of 51 samples, 55% have a muddy sand texture, while 45% of the samples have sandy mud. Pachpadra and Pokhran predominately have fine sand fractions ranging from 20.51% to 49.2% and 10.40% to 35.38%, respectively. Didwana playa is dominated by very fine sand, ranging from 14.01% to 33.31%. Sediment in playas consists of very fine to fine sand and very coarse to coarse silt. However, considerable sediment fractions of 70.65–89.56%, 65–85%, and 62–85% are obtained in Pachpadra, Pokhran, and Didwana playas, respectively.

Table 2. Descriptive statistics for the grain size parameters of Pokhran, Pachpadra, and Didwana playas (\( n = 51 \)).

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>SD</th>
<th>Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mz</strong></td>
<td>(φ)</td>
<td>3.58</td>
<td>5.11</td>
<td>4.3</td>
<td>0.35</td>
<td>3.19</td>
<td>4.68</td>
<td>3.94</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>0.0289</td>
<td>0.0835</td>
<td>0.0521</td>
<td>0.0123</td>
<td>0.0389</td>
<td>0.1096</td>
<td>0.0688</td>
<td>0.0221</td>
</tr>
<tr>
<td><strong>Sorting</strong></td>
<td>(φ)</td>
<td>1.54</td>
<td>2.23</td>
<td>1.89</td>
<td>0.17</td>
<td>1.32</td>
<td>2.15</td>
<td>1.76</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>0.0029</td>
<td>0.0047</td>
<td>0.0037</td>
<td>0.0004</td>
<td>0.0025</td>
<td>0.0045</td>
<td>0.0035</td>
<td>0.0007</td>
</tr>
<tr>
<td><strong>Skewness</strong></td>
<td>(φ)</td>
<td>0.15</td>
<td>0.45</td>
<td>0.27</td>
<td>0.09</td>
<td>0.28</td>
<td>0.49</td>
<td>0.38</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>−0.0004</td>
<td>−0.0002</td>
<td>−0.0003</td>
<td>0.0001</td>
<td>−0.0005</td>
<td>−0.0003</td>
<td>−0.0004</td>
<td>0.0001</td>
</tr>
<tr>
<td><strong>Kurtosis</strong></td>
<td>(φ)</td>
<td>0.82</td>
<td>1.13</td>
<td>0.95</td>
<td>0.07</td>
<td>0.81</td>
<td>1.44</td>
<td>1.06</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>mm</td>
<td>0.0008</td>
<td>0.0011</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0008</td>
<td>0.0014</td>
<td>0.0011</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

The higher percentage of fine fraction implies that precipitation was not the main driving factor for sediment deposition in the playas [59–61]. This region has the country’s lowest mean annual rainfall (250 mm) and faces frequent droughts [4,34]. The evapotranspiration rate exceeds the precipitation rate, which causes a negative water budget in this region. Additionally, the prevailing wind condition shows the SW direction, where we have the sources of sand dunes. Wind speeds in the region range from 5 m/s (20.5 km/hr) to 11 m/s (39.6 km/hr), which could be strong enough to drift fine sand and silt from the SW region of the playas. This supports the 77% of sand and silt obtained in the playas, and the dominance of fine sand and silt fractions in the playa’s sediments may be ascribed to the aeolian and fluvial deposition processes in different energy environments [62].
3.2. Bivariate Scatter Plots of Grain Size Parameters

The general composition of playas includes materials like silt, fine sand, clay, and evaporites. Bivariate scatter plots significantly interpret the interrelationship between mean, standard deviation, and skewness measurements to identify the process of sediment transport and deposition [10,11,63]. The relationship between mean grain size (Mz) and sorting (standard deviation) ascertains the energy change and material origin of sediment environments [64]. Figure 3 shows the plot between sorting and Mz for Pachpadra, Pokhran, and Didwana playa. Based on the Mz value, it is observed that in the Pachpadra playa, 65% of samples fall into the category of very fine sand, and the rest have very coarse silt with Mz values ranging from 3.19 to 4.68 φ. In Pokhran, 82% of samples fall into the category of very coarse silt, 12% fall into fine sand, and 6% have coarse silt texture, with a mean value of 3.58 to 5.11 φ. In Didwana, 65% of samples were very coarse silt, 23% were coarse silt, and 12% had a fine sand texture, with a mean grain size ranging from 3.69 to 5.52 φ. The analysis of the samples from Pokhran (15 out of 17), Pachpadra (8 out of 17), and

![Figure 2. Distribution of Mean Grain Size (φ) in (a) Pokhran, (b) Pachpadra, and (c) Didwana playa.](image-url)
Didwana (15 out of 17) indicate rapid deposition of sediments in a low-energy environment (Figure 3).

In contrast, the remaining samples show slow deposition in a high-energy environment. It might be a conglomeration of various depositional processes [3]. The mixed population of sediments deposited in playas suggests multiple modes of sediment transport. This also means a blended population of sediments carried by wind and fluvial activities.

Sorting suggests the intensity of forces that decide sediment distribution [65]. Mean grain size and sorting are controlled hydraulically, and lower sorting values correspond to better sorting processes in sediment samples. Therefore, best-sorted sediments have a mean grain size in the category of fine sand [66]. The results indicate that 82% of the samples were poorly sorted, while 18% were very poorly sorted. Poor to very poor sorting, with an abundance of fine-grained sediment, suggests a low-energy depositional environment. According to Friedman [67], skewness measures the asymmetry of the frequency distribution and marks the position of the mean according to the median. Figure 4 shows the bivariate plot between sorting and skewness. All the samples were positively skewed, with mean values for Pachpadra, Pokhran, and Didwana playa being 0.38 $\phi$, 0.27 $\phi$, and 0.27 $\phi$, respectively. Out of 51 samples, 26 were very fine-skewed, 24 were fine-skewed, and one sample fell into the symmetrical category. The dominance of positively skewed sediment indicated low energy activity (e.g., low wave action) in the playa [68].

The bivariate plot between skewness and kurtosis is used to interpret the genetic significance of sediment, which was sorted somewhere in a high-energy environment and further modified and transported to another environment [69]. Figure 5 shows the bivariate plot between skewness and kurtosis for Pachpadra, Pokhran, and Didwana playa. It was observed that samples lie within the platykurtic to leptokurtic range. Out of 51 samples, 17.65% fell into the leptokurtic category, 64.70% were mesokurtic, and 17.65% were platykurtic. The leptokurtic nature of sediment reflects the variations in energy conditions, and platykurtic exhibits the mixing of two populations in subequal amounts [15,17]. The dominance of mesokurtic sediments implies the constant addition of fine to coarse particles and can be categorized as a uniform energy environment during deposition [68,70].
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Figure 5. Bivariate plot between skewness and kurtosis.

3.3. Modelling and Partitioning of Aeolian and Fluvial Deposits in Playa Sediment

The sediments in playas are dominated by a mixed population of grains (Figure 6a–c) transported by aeolian and fluvial agents that produce reworked sediment. However, uncertainty in polymodal distributions makes it hard to explain depositional processes such as fluvial and aeolian [6,7,20,30,71,72]. The isolated saltation and suspended components comprised the fluvial sediment, while silt and fine components constituted the aeolian sediments. Therefore, this study uses the AnalySize end-member modelling algorithm on grain size data to evaluate the depositional processes and sedimentary environments in arid and semi-arid playas. The numerical unmixing of grain size distribution into constituent components, known as end-members, can yield valuable information about geological processes and sedimentary environments.
Many studies have advocated that aeolian deposition possesses a high and sharp modal peak (the value that occurs the most significant number of times in the mode) between 10 and 100 \(\mu m\), while in fluvial deposition, the modal peaks fall between 100 and 1000 \(\mu m\) \cite{9-11,24,27,64,73,74}. In this study, the grain size distribution was fitted with five EMs (Figure 6d) because the mean crosswise coefficient of determination \((R^2)\) versus the number of EMs is greater than 0.90 and increasing the number of EMs (6 or more) does not improve the precision of the mean complex correlation coefficient.

EM-3 (model peak of 63 \(\mu m\)) is coarser than EM-2 (model peak of 31 \(\mu m\)) and EM-1 (model peak of 8 \(\mu m\)), indicating that shorter transport pathways result in coarser grain particles to playa lakes, whereas long transport pathways result in fine-grain particles (EM-1 and EM-2) to playa lakes. Sediment fractions with \(M_z\) less than 63 \(\mu m\) in the playas indicate aeolian deposition, a wind-transported particle. Similar observations were reported by Wu \cite{75} at playa of Ebinur Lake, Arid Central Asia, and Abbasi \cite{76} at Iran’s ephemeral Baringak Lake. However, aeolian sediment is generally well-sorted and unimodal, but in the case of playa lake sediment, it was reworked by another process, resulting in poorly sorted sediment \cite{25,77,78}. The particle size in EM-5 (a model peak of 250 \(\mu m\)) is coarser than in EM-4 (a model peak of 125 \(\mu m\)), indicating that the hydrodynamic forces affecting EM-5 were stronger than those affecting EM-4. The total content of EM-4 and EM-5 can be interpreted as an indication of regional hydrodynamic processes. It was supposed to be transported by streams into the concerned area and can be linked to the prevailing hydrological conditions, such as precipitation. The precipitation would enhance soil erosion in the adjacent regions and increase the sediment transport capacity of streams.

The average fine fraction \(((EM-1) + (EM-2) + (EM-3))\) values obtained for the Pachpadra, Pokhran, and Didwana playas were 46.29\%, 66.11\%, and 66.28\%, respectively. In Pachpadra, Pokhran, and Didwana, the average coarser fraction deposition \(((EM-4) + (EM-5))\) is 53.71\%, 33.89\%, and 33.72\%, respectively. We observed that the playas contained mostly aeolian sediment transported by the wind. The finer particle distribution increased from the arid (Pachpadra) to the semi-arid (Didwana) region. Also, the increase in fine particles and decrease in coarse particles can be attributed to the aeolian deposition in

![Grain size distributions of sediment samples](image.png)

**Figure 6.** Grain size distributions of sediment samples from (a) Pokhran playa, (b) Pachpadra playa, (c) Didwana playa, and (d) Representative five EMs resulting from modelling.
Playas, where fine particles are transported long distances through winds and remain suspended for an extended period. In contrast, coarser particles travelled a short distance and remained suspended for a small period in the air. Dumka [4] and Singhvi & Kar [79] reported the arid climate (rainfall is less than 25 cm) and strong winds in this region, which experiences frequent and violent dust storms during the pre-monsoon (April-June) season, supplying aeolian sediment to playas. Pachpadra playa drains into the Luni River in the monsoon season through small streams, while the streams linked to Pokhran and Didwana playa are disconnected due to anthropogenic activities. So, we anticipated that sediment deposition in the Pachpadra playa is probably a fluvial process, while the Pokhran and Didwana playas have more aeolian input than fluvial input.

3.4. Sediment Transport and Deposition

The CM diagram [56,57] is another method used to define textural patterns and depositional processes. Sediments classified by the relationship between the coarsest one percentile particle (C) and the median particle size reflect the transporting agent’s competence. Thus, the Passega CM diagram is applied to the grain size of the sediment of Pachpadra, Pokhran, and Didwana playas.

The CM diagram suggests that sediments were deposited through the uniform suspension process in the RS region in Figure 7, except DD-9 and PK-16, which were anthropogenically disturbed. Primarily, small fractions of clay and silt (EM-1 to EM-3) are carried away from the source location in suspension to be deposited in adjacent or distant areas of playa lakes. Pachpadra, Pokhran, and Didwana playas have poor to very poor sorting in the grain size. Poorly sorted sediments are deposited through uniform suspension and are represented by segment R.S. of the CM diagram. It is also perceived that the fine silt and clay can be mixed with the coarsest fraction (EM-4 and EM-5) of the sediments in any proportion. In all samples, the sediment is a mixture of coarse to fine silt and clay in varying proportions.

![Figure 7. Sediment transport and deposition process (CM) diagram of Pachpadra, Pokhran, and Didwana playas. (adapted from Passega, 1957 and Passega and Byramjee, 1969).](image)

The playa crust is made up of thick, soluble evaporates which dissolve after precipitation. These evaporites and wet playa beds form the basis for the aeolian deposition. Deposition of sediments in the playas appears to occur mainly as a settle-out of fine sand-silt-clay-sized grains from suspension when the turbulence of the flooded water subsides. After precipitation, wind-induced waves may cause the reworking of the entire layer of sediment [11,57,68,80].

3.5. Environmentally Sensitive Grain Size Components (ESGSC)

Playas are excellent sensors of environmental change, where a small alteration in the evaporation or precipitation rates may reflect major changes in water level, salinity,
and sedimentary records. These responses are registered in the sediment and can provide high-resolution change records on many timescales [4,10,27,30,81]. The variation in the sedimentary environment can be studied by evaluating the range and proportions of grain size components. The ESGSC extracted grain size population data were also counted as a significant parameter to examine the sedimentary changes. The standard deviation values versus grain size classes are displayed in Figure 8a, and the spatial distribution of ESGSC for the three playas is illustrated in Figure 8b-d. Based on the extraction via the grain size standard deviation, three ESGSCs in Pokhran (250 µ, 31 µ, and 2 µ), three ESGSCs in Pachpadra (125 µ, 31 µ, and 4 µ), and two ESGSCs in Didwana playa (125 µ and 16 µ) were sensitively influenced by the sedimentary environment. This indicates the GSD fluctuation and the environmental changes in the regions. Wang [82] also reported a similar relationship at Chanthaburi Coast, Thailand, and Ma [70] reported in the Bosten Lake region, China. The standard deviation values and size ranges of the grain size populations in playas are different, showing that the sediment sources and how it moves between playas vary.

Figure 8. (a) Grain size vs standard deviation plot for Pachpadra, Pokhran, and Didwana playas, and distribution of environmentally sensitive grain size (ESGSC) in (b) Pokhran, (c) Pachpadra, and (d) Didwana playa.

4. Conclusions

The results of depositional environment analysis of playas gave essential information about the mode of sediment transport processes. End-member modelling determined the
sediment grain size distribution through statistical analysis. The playa sediments mainly consist of very fine sand (46–54%) and very coarse silt (22–37%). The average fine fraction of Pachpadra, Pokhran, and Didwana playa was 46.29%, 66.11%, and 66.28%, respectively. However, the average coarser fraction deposition in Pachpadra, Pokhran, and Didwana corresponds to 53.71%, 33.89%, and 33.72%, respectively, suggesting that the playas mostly contain aeolian sediment rather than fluvial sediment transported by wind.

The playa sediment is mostly composed of very fine sand and very coarse silt, with a small proportion of fine silt. EM-1, EM-2, and EM-3 suggest aeolian transport of the silt fraction, and EM-4 and EM-5 suggest local stream transport of the coarser fraction. Poor to very poor sorting and the abundance of fine-grained (less than 63 μm) sediments were inferred from the mixed population of sediments, which was transported by wind and fluvial activity, thus producing reworked sediment. Bivariate plots of mean, standard deviation, skewness, and end-member analysis resolved the dominance of aeolian and fluvial activities in the study area. The aeolian deposition was formed by the fluvial and fluvio-lacustrine deposits, suggesting that the aeolian process transports the fine particles. In contrast, the runoff from local streams (fluvial processes) deposits coarser particles in the playas. The CM pattern of sediment deposition and transport in the playas suggests that the sediment has been deposited through uniform suspension. The entire process indicates that the sediment was deposited at a moderate velocity in a very shallow, unchanneled fluvial environment. An ESGSC analysis revealed that the grain size classes 2–3 φ, 5–6 φ, and 8–9 φ had high standard deviations and were environmentally sensitive grain size components, indicating the spatial variability of sediment sources and transport processes between these playas. The ESGSC in Pokhran (250 μ, 31 μ, and 2 μ), and Pachpadra (125 μ, 31 μ, and 4 μ), while two ESGSCs in Didwana playa (125 μ and 16 μ) indicate that the sediments were deposited with moderate velocity in a low energy environment with a mixed sediment population transported by aeolian and fluvial activity.

The lack of elemental data limits the study. If the grain size algorithm were combined with the elemental data and mineral assemblages, it would have been easier to figure out the sediment source, transport process, and depositional environment.

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**References**


69. Folk, R.L. A review of grain-size parameters. Sedimentology 1966, 6, 73–93. [CrossRef]


75. Wu, N.; Ge, Y.; Abuduwaili, J. Grain Size Characteristics of Sediments Found in Typical Landscapes in the Playa of Ebinur Lake, Arid Central Asia. Land 2021, 10, 1132. [CrossRef]

76. Abbasi, H.R.; Opp, C.; Groll, M.; Rohipour, H.; Khosroshahi, M.; Khaksarian, F.; Gohardoust, A. Spatial and temporal variation of the aeolian sediment transport in the ephemeral Baringak Lake (Sistan Plain, Iran) using field measurements and geostatistical analyses. Z. FörGeomorphol. 2018, 61, 315–326. [CrossRef]


