RESEARCH PAPER

DESERT OASES AS GEOHERITAGE-RICH AREAS: PRESENT KNOWLEDGE AND SUSTAINABILITY PERSPECTIVES IN THE WESTERN DESERT OF EGYPT AND BEYOND

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ABSTRACT. Contemporary progress in geological heritage (geoheritage) studies in deserts has allowed the identification of a new resource for sustainable development in oases. The field investigations and the bibliographical survey enable the identification of geoheritage-rich areas (GRA) in the Western Desert of Egypt and beyond. These GRAs reflect natural concentrations of peculiar geological and geomorphological features. Eight oasis-centered GRAs are outlined in the Western Desert of Egypt (Bahariya, Dakhla, Dungul, Faiyum, Farafra, Kharga, Kurkur, Siwa), and several GRAs of the same kind are found in North Africa (beyond Egypt), the Middle East, and western South America. The Egyptian GRAs often represented sedimentary, paleogeographical, and geomorphological features. It is established that these GRAs differ in geoheritage exploration and content, and the most comprehensive data are available for four oases of the Western Desert of Egypt (Bahariya, Farafra, Faiyum, and Siwa) and the Hingol area of Pakistan. It is argued that various sustainability aspects matter for the considered oases of the Western Desert of Egypt and can be linked to the United Nations Sustainable Development Goals. Utilization of geoheritage resources can contribute to the sustainability of desert oases. It is also suggested that geoheritage studies in the oases of the Western Desert of Egypt can serve as a model for similar research in other desert domains of the world.

KEYWORDS: arid environments, geosites, North Africa, research geography, sustainable development

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INTRODUCTION

Oases play a vital role in arid and hyper-arid areas of the world. They diversify desert environments and make them habitable. It would be difficult to imagine agriculture, long-distance transportation, and tourism in deserts without oases. Their historical role was outstanding (Moore et al. 1994; Mattingly et al. 2015; Guagnin et al. 2017; Rowlands et al. 2020; Manapova 2021; Fenwick et al. 2021; Kaczmarek et al. 2024). Scientists pay a much greater attention to contemporary development, planning, and sustainability of oases (Xiao-feng and Zhe 2001; Bouaziz et al. 2018; Xue et al. 2022; Chen et al. 2023; Dhawi and Aleidan 2024) in such different regions as North Africa (Amichi et al. 2020; El-Hassanin et al. 2020), Central Asia (Bie and Xie 2020; Zhang et al. 2023), and western South America (Calderón-Seguel et al., 2021). However, the full potential of sustainable development in oases with novel types of natural resources is yet to be fully understood.

In the early 21st century, researchers recognized that geological heritage (geoheritage), which refers to peculiar geological and geomorphological features of a given territory, can be treated as an important natural (geological) resource (Bétard et al. 2017; Singtuen et al. 2019; Custódio et al. 2024; Mousa et al. 2024; Sen et al. 2024). Its conservation (geoconservation) and utilization (first of all, geotourism) contribute to sustainable development and bring socio-economic benefits (Prosser et al. 2013; Dowling and Newsome 2018; Reynard and Brilha 2018; Kubalíková et al. 2021; Xu and Wu 2022; Bressan and Lopes 2023; Soldati 2023). Beyond nature protection, enhanced education, and tourism initiatives, which are often discussed in the literature (Gupta et al. 2024; Zafeiropoulos et al. 2025), effective geoheritage management has some other important implications for sustainability. They include (but are not limited to) better awareness of traditional and renewable natural resources as an outcome of geoheritage inventories, development of transport infrastructure related to initiatives of accessibility improvement, and deeper understanding of identities of local communities rooted in heritage and symbolic meaning of geological/geomorphological objects. Importantly, many geoheritage-rich areas host sources of freshwater or serve as habitats for unique plants and animals.

Geoheritage features are rather abundant in desert domains due to better exposure and visibility of geological and geomorphological features where vegetation is scarce or absent. Although sand and coarse debris can mask these features, the former themselves are geological phenomena and even elements of geoheritage. Inventories of geoheritage in different deserts of the world constitute an urgent task (cf. Sayama 2024).

Five reasons why oases can become targets for geoheritage studies can be outlined. First, oases are often rich in peculiar geological and geomorphological features because their existence is determined by specific geological and geomorphological settings. Second, oases retain connections with populated areas beyond deserts, and thus, they have better accessibility than other desert areas. Third, the presence of settlements in many oases makes accommodation of geoheritage researchers comfortable possible and facilitates their work by the availability of earlier accumulated geological knowledge and education centers (even universities). Fourth, many oases are distinguished by outstanding scenery, which strengthens aesthetic properties of geoheritage features and attracts visitors. Fifth, many oases have been populated for centuries, and, thus, they possess rich cultural and historical heritage that requires conservation efforts and sustainable tourist flows, which facilitate the initiation of geoconservation and geotouristic initiatives. Overall, oases can be considered geoheritage-rich areas (GRAs). Naturally, oasis-centered GRAs are not only valuable but also fragile due to desert dynamics (e.g., dune migration) and intense anthropogenic intervention (e.g., agricultural activities or abundant construction).

Countries of North Africa, including Egypt, have demonstrated significant acceleration in geoheritage studies from the mid-2000s, when the related knowledge was very limited and chiefly preliminary and qualitative (Schlüter 2006), to the beginning of the 2020s, when this knowledge had become rather extensive, detailed, and based on both qualitative and quantitative studies (Neto and Henriques 2022; El hamidy et al. 2024; Errami et al. 2024). Notably, the first works on Egyptian geoheritage appeared before a research "boom" of the past decade (Shata 1988; Coli et al. 2011; El-Asmar et al. 2012; Salama et al. 2013). The development of advanced geotourism in Egypt is a current priority (Soliman and Abou-Shouk 2017). A vast area between the Mediterranean coast in the north, the western and southern boundaries of the country, and the Nile valley in the east is covered by the Western Desert of Egypt. Many oases in this region are large in size, and they have become targets of intense geoheritage studies (e.g., Plyusnina et al. 2016; Salama et al. 2020; Khalaf 2022).

The present paper aims to provide summarized knowledge about the oases-centered GRAs of the Western Desert of Egypt. This study employs published information and the authors' research experience. Oasis-centered GRAs beyond Egypt are also addressed in this study. This study evaluates the potential contribution of geoheritage to oasis sustainability.

STUDY AREA

The Western Desert of Egypt is a northeastern segment of the Sahara with hyper-arid environments. Groundwater discharge via springs in topographic depressions supports the existence of lakes, streams, and even waterfalls. The availability of water makes agriculture possible in these depressions, which are oases. Several relatively large oases are located in the Western Desert of Egypt (Fig. 1). Many of them are populated and possess settlements of varying size. El-Kharga City is an example of an important and growing administrative and educational center in the middle of the desert. Some oases, such as Siwa Oasis, attract numerous tourists. The oases are connected to the Nile Valley and the Mediterranean coast by roads, including paved roads of high quality with regular public transportation.

The geological setting of the Western Desert of Egypt and its oases is diverse (Crombie et al. 1997; Brook et al. 2003; Guiraud et al. 2005; Issawi et al. 2009; Tawadros 2011; Aly 2015; Said 2017; Hamimi et al. 2020, 2023; Peroschi and Cambieri 2023; Mansour et al. 2024). This territory is the northeastern edge of the African lithospheric plate, and it has been relatively stable during the entire Phanerozoic despite certain deformations and faulting. The sedimentary succession of the Western Desert is dominated by Cretaceous–Paleogene siliciclastics and carbonates that accumulated during marine ingressions from the north. Continental (including alluvial) facies are also present. Precambrian crystalline and Paleozoic sedimentary rocks, as well as igneous bodies, crop out locally. Quaternary deposits are represented particularly by sand dunes, although carbonates that formed during wetter climate phases are also present. Paleontological remains are abundant in some sedimentary packages. Mineral deposits and groundwater are important geological resources, which have been exploited for local and national needs.

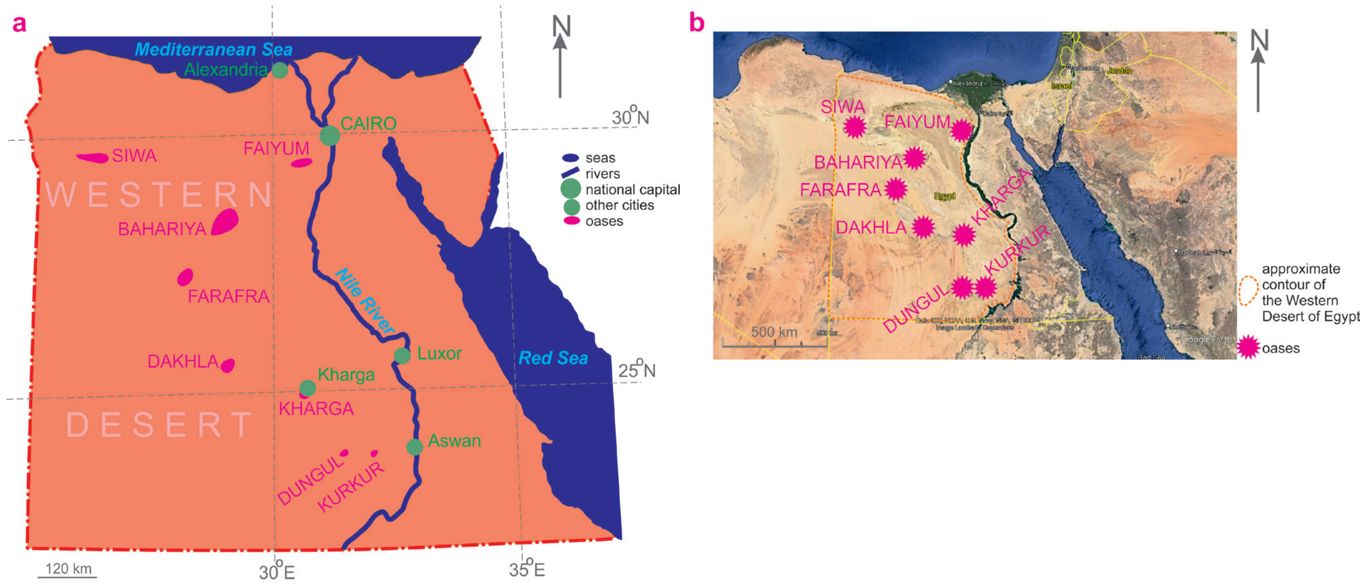

Fig. 1. Geographical location of the considered oases of the Western Desert of Egypt: a – general location map, b – satellite image[1]

[1] Source: Google Earth Pro.

MATERIALS AND METHODS

Data collection

Field investigations in the majority of the oases of the Western Desert of Egypt, including assessments of geoheritage resources and inventories of geoheritage sites (geosites) were carried out over approximately a decade. The related observations and interpretations validate published knowledge of oasis geoheritage. This field-based information is essential to establish common geoheritage types and assess the completeness of the knowledge of geoheritage of each oasis.

The information about oases-centered GRAs beyond Egypt is scattered in the literature, and, thus, a selection of the relevant sources is an urgent task. The bibliographical database "Scopus", which covers scientific journals regularly publishing outcomes of geoheritage studies, was used for this purpose. A carefully constructed search formula allowed identification of the principal sources, from which irrelevant ones were then deleted (Fig. 2). Indeed, the obtained set of works cannot be exhaustive (this is typical of all bibliographical surveys), but the sample is sufficient for the present analysis. The full text of each relevant source was checked to systematize the knowledge of oases-centered GRAs.

Basic procedures

Descriptions of geoheritage of the considered oases of the Western Desert of Egypt and beyond can be found in the literature (summarized below). They are not repeated in the present work, although some distinctive features and the compiled lists of sources are provided. Attention is paid to two general characteristics of GRAs, namely geoheritage exploration and main geoheritage types. These characteristics reflect "maturity" and content of the considered GRAs.

Although the basic principles of a territorial geoheritage assessment and inventory are well-developed (Prosser et al. 2006; Reynard and Brilha 2018; Song et al. 2023; Štrba et al. 2023; Zorlu et al. 2023; Ferrer et al. 2024; Kubalíková 2024), the really used approaches may differ significantly depending on research tasks, accessibility, and natural contexts. The published studies dealt with:

1) A single geosite of a given area;
2) A few geosites (randomly selected or sharing common attributes) of a given area;
3) As many geosites of a given area as possible;
4) Potential existence of geosites;
5) Diversity of local geological and/or geomorphological phenomena and possible geoparks.

The knowledge of each given GRA develops individually, and it is characterized by distinct certainty and completeness. For the purposes of the present analysis, the options used in the previous geoheritage studies were detected.

The content of GRAs is reflected by an attribution of peculiar geological and geomorphological features available there to standardized geoheritage types. The employed nomenclature of the latter follows Ruban (2020) and includes geomorphological (landforms), tectonic (structures), stratigraphical (stratotype sections, unconformities), paleontological (fossils), sedimentary (sedimentary phenomena), paleogeographical (facies, paleoecosystems), igneous (magmatic phenomena), metamorphic (metamorphic phenomena), geochemical (geochemical anomalies), mineralogical (mineral localities), hydro(geo)logical (surface water, springs, groundwater), geothermal (hot springs, geysers), engineering (active slopes), pedological (soils), economical (mineral and energy deposits), geohistorical (history of geological exploration), geocryological (permafrost), cosmogenic (impact structures), and complex (co-existence of two and more types) types. Many types co-exist in GRAs, but the information on their number depends on the previous research (for instance, some specialists focused only on particular features and ignored the others). Moreover, the value of features belonging to different types can vary. To make the knowledge of the content of the considered GRAs consistent, three main (most valuable and characteristic) types were outlined for each oasis. Selection of these types required a careful analysis of the published information.

RESULTS

Western Desert of Egypt

A total of eight oasis-centered GRAs can be identified in the Western Desert of Egypt (see Fig. 1). In two cases, the oases are paired, and the related GRAs are close to one another. The large Bahariya and Farafra oases are located in the northern half of the desert. They possess diverse geological features, the most interesting of which include late Mesozoic–Cenozoic sedimentary rocks and the related facies, as well as karst features. The Dakhla Oasis is situated in the central part of the desert, and it is known for peculiar landforms (natural "sculptures") and specific sedimentary rocks and facies such as Late Cretaceous variegated shales (Fig. 3a). The Dungul and Kurkur oases are small, and they are found on the southeastern edge of the desert. They are famous for spectacular paleospring

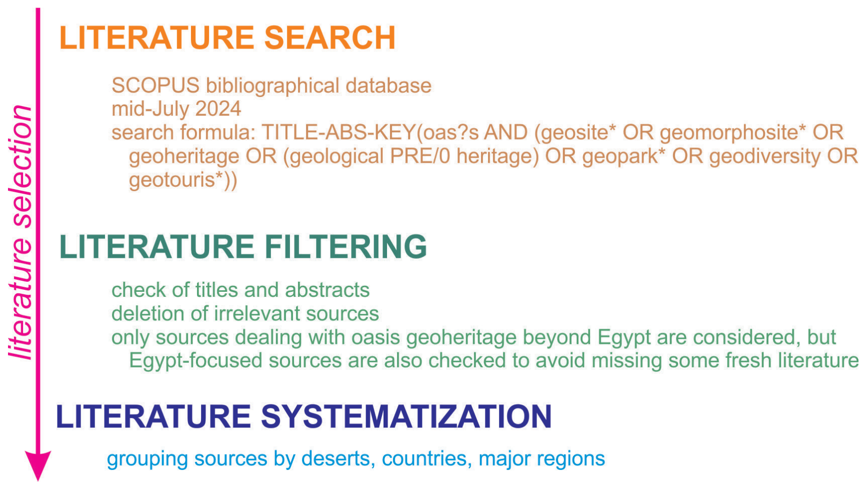

Fig. 2. Procedures of literature selection for the purposes of the present study

tufa deposits of Quaternary age overlying older deposits (Fig. 3b). The Faiyum Oasis on the northeastern edge of the desert is not only large and well-populated but also the most proximal to the Nile Valley, with which it has been strongly connected since ancient times. It is well-known to paleontologists due to impressive and well-preserved skeletons of Paleogene marine vertebrates (whales) (Fig. 3c), findings of which have made this locality emblematic of the entire Egyptian geoheritage. The Kharga Oasis is large and elongated, and it is situated in the eastern part of the desert. Characteristic features include tufa deposits of ancient springs indicating much wetter conditions in the Quaternary (Fig. 3d). Finally, the Siwa Oasis lies in a deep depression (below sea level) in the northwestern part of the desert, and it is famous for its rich cultural history going back to the pharaonic kingdoms and Alexander the Great. Geologically, it is known, primarily, for outcrops of Miocene carbonate rocks (Fig. 3e) and active evaporite deposition in several lakes (Fig. 3f).

The analysis of the published studies shows that the considered oases of the Western Desert of Egypt differ in geoheritage exploration (Table 1). The information on the GRAs corresponding to the Bahariya, Farafra, Faiyum, and Siwa oases appears most certain and complete. On the one hand, their geoheritage potential was studied comprehensively. On the other hand, many geosites were already proposed. In the cases of the Dungul and Kurkur oases, the situation is different. There, the geoheritage potential was examined with similar attention, but only selected geosites were proposed, and they were neither described formally nor assessed. Therefore, additional investigations are necessary to expand the information in these GRAs. The quality of information on Kharga and especially Dakhla oases is poorer. In the former, almost

Fig. 3. Examples of geoheritage from the different oases of the Western Desert of Egypt: a – a small isolated landform exhibiting Campanian (Cretaceous) variegated shales (Dakhla Oasis), b – Quaternary tufa deposits overlying unconformably Maastrichtian (Cretaceous) shales (Dakhla Formation), c – a skeleton of an Eocene (Paleogene) cetacean (Faiyum Oasis), d – exposures of Quaternary tufa deposits indicating a wetter local paleoclimate (Kharga Oasis), e – Miocene (Neogene) carbonates exposed on slopes of a large residual hill (Siwa Oasis), f – coast of the Siwa lake (Siwa Oasis). All photographs were made by E.S. Sallam

randomly established geosites were proposed, and a single geosite was proposed in the latter. Thus, these GRAs need analyses of their geoheritage potential, and more geosites can be found there. Full-scale, field-based investigations are necessary to fill these gaps. The summarized evidence suggests that simultaneous or successive geoheritage studies by two or more research teams in the same oasis-centered GRAs and applications of different approaches have led to more robust and comprehensive knowledge.

The content of the GRAs in the Western Desert of Egypt differs. Sedimentary, paleogeographical, and geomorphological types are the most common geoheritage types. However, the Bahariya, Faiyum, and Siwa oases possess some other types (igneous, paleontological, and hydro(geo)logical types, respectively), which are important only in them. The detailed analysis of the works dealing with the considered GRAs (see sources in Table 1) implies that almost all geoheritage types exist in the Western Desert of Egypt, except for the geocryological type (indeed, permafrost is improbable in hyper-arid environments) and the cosmogenic type (more research is necessary to realize a presence/absence of impact structures in this desert). The quantity of information from the Dakhla and Kharga oases does not permit documentation of the range of geoheritage types.

Beyond Egypt: Africa and the rest of the world

Several oases-centered GRAs exist beyond Egypt (Table 2). Half of them are situated in North Africa (Morocco and Tunisia), 40% are located in the Middle East, and a single GRA is known from western South America (Chile). Indeed, many oases exist in the deserts of Australia, Central Asia (especially western China), western North America, and South Africa; Antarctica is also a desert with oases, although of a different type. This suggests that either the corresponding geoheritage has yet to be explored or its relevance to oasis environments was not stressed in the publications. Nonetheless, a quasi-global occurrence of oasis-centered GRAs is evident despite the noted knowledge gaps.

The considered oasis-centered GRAs established beyond Egypt differ in geoheritage exploration (Table 2). The only Hingol area of Pakistan boasts really comprehensive information about its geoheritage resources. In many cases, attention was paid to either particular geosites or particular geoheritage types (e.g., geomorphological). From two GRAs, only single geosites (although large and complex) were reported. Generally, the quality of the information is moderate, with uncertainties (when only potential was considered) or incompleteness (when only a few geosites were proposed). The sources indicated in Table 2 show significant differences in the approaches and researchers' goals. Notably, a few works discuss either established or proposed geoparks.

The content of the considered GRAs differs. The geomorphological and sedimentary types are the most common geoheritage types, and the paleogeographical and hydro(geo)logical types are also rather frequent. One should note that more than a half of the considered GRAs represent the types other than those above-mentioned.

DISCUSSION

Sustainability perspectives: a conceptual ground

Various aspects of sustainability linked to various Sustainable Development Goals specified by the United Nations (Wackernagel et al. 2017; Leal Filho et al. 2019; Bandari et al. 2022; Jarrah et al. 2024; Raman et al. 2024),

Table 1. Geoheritage in the oases of the Western Desert of Egypt. The knowledge is valid for mid-2024. See the location of the oases in Fig. 1

Oasis (area, km^2; main settlement)	Geoheritage exploration*	Three main geoheritage types	Remoteness from the Nile valley	Source(s)**
Bahariya (~2000, El Bawiti)	Assessed resources	Sedimentary, paleogeographical, igneous	Significant	Salama et al. (2013), Plyusnina et al. (2016), Khalaf et al. (2019), Mousa et al. (2023)
Dakhla (~2000; Mut)	Single geosite proposal	Geomorphological, paleogeographical, sedimentary	Significant	AbdelMaksoud et al. (2020)
Dungul (~22; uninhabited)	Several geosite proposals; potential revealed	Sedimentary, paleogeographical, geomorphological	Significant	Sallam et al. (2018b)
Faiyum (~1700; Faiyum city)	Assessed resources	Paleontological, paleogeographical, geomorphological	Moderate	Sallam et al. (2018a); Khalaf and El-Kheir (2022)
Farafra (~1000; Farafra city)	Assessed resources	Sedimentary, paleogeographical, geomorphological	Very significant	Plyusnina et al. (2016), Salama et al. (2020), Khalaf (2022), Mousa et al. (2023)
Kharga (>5000; El Kharga city)	Several geosite proposals	Sedimentary, paleogeographical, geomorphological	Significant	Mousa et al. (2024)
Kurkur (>30; uninhabited)	Several geosite proposals; potential revealed	Sedimentary, paleogeographical, geomorphological	Significant	Sallam et al. (2018b)
Siwa (~200; Siwa city)	Assessed resources	Hydro(geo)logical, sedimentary, paleogeographical	Very significant	Sallam et al. (2018a), Ahmed (2023)

Notes:
*See text for more explanations.
**Due to the engagement of the authors in geoheritage studies in all mentioned oases, they cite a minimal number of their own works.

Table 2. Geoheritage in the desert oases beyond Egypt. The knowledge is valid for mid-2024

Oasis or oasis-related area (country; abbreviation)	State of geoheritage exploration*	Three main geoheritage types*	Geopark options*	Source
Al-Ahsa (Saudi Arabia)	Single geosite proposal	Geomorphological, engineering, sedimentary	No	Sen et al. (2023)
Azraq (Jordan)	Briefly characterized potential	Hydro(geo)logical, igneous, sedimentary	Proposed	Mohammad et al. (2023)
Errachidia (Morocco)	Several geosite proposals	Tectonic, paleogeographical, geomorphological	No	Si Mhamdi et al. (2023)
Hingol (Pakistan)	Assessed resources	Sedimentary, geomorphological, stratigraphical	Proposed	Yaseen et al. (2021)
Jebel Hafit (UAE)	Single geosite proposal	Geomorphological, tectonic, paleogeographical	No	Giusti et al. (2023)
Nefzaoua (Tunisia)	Partly assessed resources	Hydro(geo)logical, geomorphological, economic	No	Raddadi and Podwojewski (2022)
Oued Noun (Morocco)	Several geosite proposals	Sedimentary, hydro(geo)logical, igneous	No	Mirari and Benmlih (2021)
Pica (Chile)	Partly assessed resources	Hydro(geo)logical, sedimentary, geomorphological	No	Lictevout et al. (2020)
Tata (Morocco)	Briefly characterized potential	Paleogeographical, geomorphological, sedimentary	Established	Berred and Berred (2021)
Tozeur (Tunisia)	Several geosite proposals	Geomorphological, paleogeographical, economic	No	De Waele et al. (2005)

Note:
*These characteristics follow the only indicated sources.

were reported from the majority of the considered oases of the Western Desert of Egypt. Their diversity is impressive, and the majority of these aspects are linked to sustainable agriculture, water, and energy (Table 3). Similarly, some aspects of sustainability were addressed in oasis-centered GRAs beyond Egypt (e.g., Mohammad et al., 2023). Sustainable development in oases requires the use of all relevant resources available locally. The previous research in Egypt (e.g., Sallam et al. 2018a; Khalaf et al. 2019) and beyond (De Waele et al. 2005; Si Mhamdi et al. 2023) has stressed that geoheritage is among such resources.

The idea of GRAs indicates that oases do not possess but concentrate geoheritage resources and make their effective exploitation possible. There are many directions and opportunities to use these resources, and this exploitation can contribute to sustainable development more rapidly (Fig. 4). For instance, many oases need improvements in agricultural practices (regarding land degradation) and groundwater management (Table 2). If rich geoheritage resources are available, their use will almost automatically require better local planning, which requires improvements in overall environmental management. Experts with advanced knowledge and skills will be engaged in such planning. Moreover, financial benefits from geoheritage-triggered tourism (not only geotourism) will extend locally available funds for innovative environmental management. In such a situation, the potential for positive changes in agriculture and groundwater use increases.

The presence of geoheritage resources in the Western Desert of Egypt and many other arid/hyper-arid areas was recognized relatively recently, and, thus, the use of these resources for sustainable development can only be proposed. It would be difficult to register actual cases. Nonetheless, two conceptual examples can be provided. First, the use of geothermal resources for energy generation and sustainable transition has remained on the agenda in the Western Desert of Egypt (Abdel Zaher et al. 2018; Elmasry et al. 2022) and its oases (Mohamed and Zaher 2020; Arafa-Hamed et al. 2023; Ghoneim et al. 2023). The related developments depend on the understanding of the local geological settings. The latter can be determined much more precisely in the course of geoheritage investigations requiring accurate documentation and inventory of small-scale features. Second, Soliman and Abou-Shouk (2017) noted government interest in the development of non-traditional tourism, to which geotourism also belongs, and the attraction of international visitors. Indeed, the related activities require a full-scale exploration of geoheritage resources, as well as their active promotion. Considering behavioral attributes of foreign tourists (Soliman and Abou-Shouk 2017) will contribute to geotourism growth.

Two examples demonstrating the already started contribution of oases-centered GRAs to sustainable development can also be proposed. First, several GRAs, such as the Bahariya and Faiyum oases, have already been used for enhancing education. Particularly, field educational campaigns were organized for university students, and geosites representing "ideally" some geological phenomena and concepts served ideally in the explanations of these phenomena and concepts. This not only strengthened knowledge and skills and contributed to more professional and, thus, sustainable exploitation of the geological environment but also cultivated better awareness of Egyptian geoheritage, which is related to national pride. Second, the UNESCO World Heritage Site Wadi El Hitan in the Faiyum Oasis has fostered international collaboration of scientists and, thus, strengthened the inflow of intellectual capital to the country. It should be noted that accumulation of such capital correlates with environmental sustainability (Delgado-Verde et al. 2025; Gidage and Bhide 2025). As stated by Gingerich (2024), this geosite has outstanding importance to science

Table 3. Examples of the sustainability aspects in the oases of the Western Desert of Egypt

Oasis*	Sustainability aspect	Theme	Related UN SDG**,***	Source(s)
Bahariya	Geothermal potential	Sustainable energy	SDG7: Affordable and clean energy	Mohamed and Zaher (2020)
	Groundwater quality and vulnerability	Sustainable water	SDG6: Clean water and sanitation	Masoud and El Osta (2016), Sharaky and Abdoun (2020)
Dakhla	Soil erosion	Sustainable agriculture	SDG2: Zero hunger	Selmy et al. (2021)
	Possible groundwater depletion			Kimura et al. (2020)
Faiyum	Cultivated land degradation / land use changes	Sustainable agriculture	SDG2: Zero hunger	Ali et al. (2013), Atef et al. (2024)
	Quality of life concerns	Sustainable people's life	SDG3: Good health and well-being	El Sary and El-Sherbiny (2024)
	Lake productivity	Sustainable fishery	SDG14: Life below water	Napiórkowska-Krzebietke et al. (2016), Mohamed et al. (2022)
	Tourism sustainability potential	Sustainable tourism	SDG12: Responsible consumption and production	Ramzy (2013)
Farafra	Geothermal potential	Sustainable energy	SDG7: Affordable and clean energy	Arafa-Hamed et al. (2023)
	Urban sustainability solutions			Abouelfadl et al. (2014)
	Desertification / land degradation	Sustainable agriculture	SDG2: Zero hunger	Abuzaid et al. (2021), Fadl et al. (2022)
	Groundwater management	Sustainable water	SDG6: Clean water and sanitation	Moharram et al. (2012)
Kharga	Agricultural water use	Sustainable agriculture	SDG2: Zero hunger	El-Shirbeny et al. (2021)
	Renewable sources of electricity production (wind power)	Sustainable energy	SDG7: Affordable and clean energy	Ahmed (2019)
Siwa	Geothermal potential	Sustainable energy	SDG7: Affordable and clean energy	Ghoneim et al. (2023)
	Tourism, local communities, environment	Sustainable tourism	SDG12: Responsible consumption and production	Ayad and Ye (2012), Tawfik (2016), Elgammal (2022)
	Lake bioinvasion	Sustainable fishery	SDG14: Life below water	Saber et al. (2022)
	Groundwater use	Sustainable agriculture	SDG2: Zero hunger	Moghazy and Kaluarachchi (2021)
	Maximizing crop production			Moghazy and Kaluarachchi (2020)

Notes:
*The information was found for only some oases of the Western Desert.
**UN SDG is a United Nations Sustainable Development Goals[2].
***The possible relations of the registered sustainability aspects and themes to the UN SDG are interpreted for the purposes of this study.

[2] Source: https://sdgs.un.org/goals.

Fig. 4. Conceptual representation of the importance of GRAs for sustainable development of oases. The ideas are based on the authors' own and previous interpretations (see sources summarized in Tables 1 and 2)

and public education due to excellent representation of Eocene tropical ecosystems. Indeed, learning about them contributes to the understanding of environmental sustainability and, particularly, the ideas of global climate changes and their wide environmental effects.

Indeed, the possible utility of oasis-centered GRAs to sustainable development is a conceptual idea (see Fig. 4). Two practical questions are who can launch the supposed initiatives and how. First, geoheritage resources of oases should be explored much better, which requires a regular activity of several research groups. If so, state, regional, and municipal governments and other official authorities interested in sustainable development should create opportunities (official research initiatives and grants, logistic support) for geoheritage studies in oases. Second, the ideas of geoheritage need better circulation among the national scientific community and tourism professionals in Egypt. Geologists should be ready to use the information generated by geoheritage experts, and tourist firms should be ready to launch geotourism programs. Third, the relevance of geoheritage resources to the sustainable development of oases needs comprehensive investigations, and the outcomes of this research have to be communicated to national and local policymakers. Indeed, only large, multidisciplinary, and government-supported project(s) can enable the achievement of these tasks. Research and educational institutions already existing in the oases of the Western Desert of Egypt can play a leading role. Mousa et al. (2024) already stressed the importance of New Valley University in the Kharga Oasis.

Geoheritage studies in the Western Desert of Egypt as a model

A comparison of the knowledge of the oasis-centered GRAs of the Western Desert of Egypt (Table 1) and the rest of the world (Table 2) implies that the former performs well in terms of the number of such GRAs and the quality of information about them. Indeed, geoheritage studies in Egypt have already developed a systematic vision of the national geoheritage. Different approaches have been permitted to address multiple aspects of geoheritage resources. These are premises to propose the Western Desert as a model for geoheritage studies in oases.

Three basic features of the above-mentioned model are as follows. First, an oasis is understood as a concentrator of geoheritage features in a desert environment, and it is studied entirely, as well as its vicinities. Second, more general and more specific geoheritage-related projects are realized simultaneously or successively. Third, geoheritage studies do not miss other kinds of natural and cultural heritage of oases (it is a norm when geological and cultural heritage coincides (e.g., Sallam et al. 2018a, b)) and pay attention to sustainability aspects (see Table 3). More generally, a comprehensive exploration of the geoheritage of deserts is reasonable to start from oases, expanding investigations to spaces around and between them.

Achievements in the understanding of the oasis-centered GRAs in the Western Desert of Egypt (see Table 1) deserve comparisons to the experience in some other countries (see Table 2). This task can be achieved via special workshops or international collaborative projects.

CONCLUSIONS

The present summary of the knowledge of geoheritage from several oases of the Western Desert of Egypt and some other regions of the world permits three general conclusions:

1) oases concentrate diverse geoheritage features;

2) a total of eight GRAs known from the Western Desert of Egypt differ in geoheritage exploration and content, and the same is true for GRAs in the other regions of the world;

3) GRAs of the Western Desert of Egypt can be related to sustainable development of oases.

The perspectives for future investigations are linked, particularly, to studying geoheritage distribution in oases, relations between geoheritage and sustainability, and opinions of stakeholders in the fields of geoheritage management and sustainable development. Understanding the suitability of oases for the creation of geoparks is also an important research task.

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