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ACHIEVING SUSTAINABLE DEVELOPMENT IN LIBYA THROUGH KARST GEOCHEMISTRY

Osama R. Shaltami [1], Mustafa A. Ben Hkoma[2*], Mohamed M. Dulayoum[3], Abobakar E. Algomati[4], Firas Khamis Muhammed[5], Kamal Abraheem Almahdi[6]

[1] Department of Earth Sciences, Faculty of Science, Benghazi University, Libya
[2] Libyan Centre for Studies & Researches in Environmental Sciences & Technology
[1] Libyan Centre for Sustainable Development Researches
[4] Department of Engineering Geology, Faculty of Engineering, University of Bright Star, Libya
[5, 6] Department of Earth Sciences, Faculty of Science, Omar Al-Mukhtar University, Libya
[3] Libyan Center for Olive Tree Research - Libyan Authority for Scientific Research

*Corresponding author: E-mail addresses: m_hkoma2017@yahoo.com

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ABSTRACT

Background: Karst in Libya is primarily found in the Al Jabal Al Akhdar region and Benghazi plain in the northeast. Karst is also observed in the Tripolitanian pre-desert region in the northwest and the Tibesti Mountains in the south. Accomplishing sustainable development in Libya through karst geochemistry involves a three-pronged approach: water resource management, hazard mitigation, and eco-tourism, all supported by ongoing scientific research. Karst systems are vital for identifying and protecting groundwater resources, which are crucial for water supply in Libya. Geochemical analysis helps monitor water quality and vulnerability to pollution, enabling better management of these resources and mitigation of hazards. Furthermore, a deeper understanding of karst systems supports the creation of geoparks and a sustainable tourism industry that conserves the environment and engages local communities. **Results**: Karst features in Libya are primarily concentrated in the Al Jabal Al Akhdar and Benghazi Plain regions, with secondary occurrences in the Tripolitanian pre-desert and Tibesti Mountains. Crucially, karst aquifers serve as vital but highly vulnerable groundwater sources, facing significant threats from pollution, overexploitation, and geomorphological hazards, necessitating urgent intervention. To address this, the study identifies a three-pronged approach for sustainable development: water resource management, hazard mitigation, and eco-tourism. Furthermore, the paper highlights that geochemical analysis is fundamental for monitoring water quality, tracing pollutant transport, and accurately delineating vulnerable zones within these complex systems. **Conclusion**: The paper concludes that karst geochemistry is essential for understanding and protecting Libya's vulnerable water resources, particularly in the critical Al Jabal Al Akhdar and Benghazi regions. To ensure sustainability, the primary recommendation is the immediate implementation of sophisticated monitoring networks and vulnerability mapping tools, alongside the development of specialized climate change adaptation strategies, all aimed at comprehensively understanding the hydrodynamic behavior and preserving the integrity of these sensitive karst ecosystems.

1. INTRODUCTION

Karst describes a landscape shaped by the dissolution of soluble bedrock like limestone, marble, and gypsum, leading to unique features. This process creates underground drainage systems where water can flow rapidly through conduits, making these aquifers highly productive but also vulnerable to contamination (e.g., Viles, 2003; Novel et al., 2007; Waele et al., 2011, 2015; Szczygieł et al., 2018; Onac and van Beynen, 2021; Zerga, 2024; Hong et al., 2026). Karst in siliceous rock is a phenomenon where landforms like caves, sinkholes, and towers form in very insoluble siliceous rocks over long periods of time, unlike classic karst that forms in soluble rocks like limestone. This "siliceous karst" is driven by processes that enhance the slow dissolution of the rock, often due to factors like acidity from organic acids in rain, specific mineral content, high rainfall, and long-term weathering (e.g., Piccini, 1995; Vaqueiro-Rodríguez, 2004; Vasconcelos et al., 2013; Hardt et al., 2022). Karst landscapes are ecologically and biologically important due to their role in providing freshwater habitats and aquifers for drinking water, and for supporting diverse and unique life forms adapted to both surface and subterranean environments. They are critical for biodiversity conservation because they harbor specialized species and endemic organisms, and also play a significant role in global carbon cycling (e.g., Struebig et al., 2009; Forti, 2015; Li et al., 2021; Stanković, 2023; Tarkowska-Kukuryk et al., 2025). Karst areas contain a wide variety of mineral resources, including placers of gold, tin, copper, uraniulrl, mercury, vanadium, iron, manganese, antimony, wolframite, columbite, tantalite, bauxite, leadzini, phosphorite, diamond, ruby, sapphire, spinel, barite, fluorite, onyx marble, clays, clay pigments, sands, coal, and peat. The fluid deposits comprise water, oil, and gas. (Filippov, 2004). Karst landscapes have significant hydrological importance due to their unique ability to store and transmit large amounts of groundwater, which serves as a vital source of freshwater for a quarter of the world's population. They are also characterized by rapid water movement through underground conduits, leading to unique hydrological processes, but making them highly vulnerable to pollution because of the lack of natural filtering. Karst hydrology is crucial for both providing drinking water and for understanding complex water systems, though it presents challenges for water management due to its sensitivity (e.g., White, 2002; Jukić and Denić-Jukić, 2006; Long, 2009; Naughton et al., 2012; Lipar and Ferk, 2015; Braitenberg et al., 2018; Bartolomé et al., 2021; Peng et al., 2025). Karst is critically important for oil and gas because it forms significant hydrocarbon reservoirs, with up to 50% of global reserves found in carbonate rock, often within karst systems. The dissolution and fracturing in karst landscapes create porous and permeable spaces where oil and gas accumulate, and understanding karstification is essential for exploration and development (e.g., Chaojun et al., 2010; He et al., 2013; Dai et al., 2017; Almalikee et al., 2020; Hao et al., 2023; Wang et al., 2025). Karst's cultural importance stems from its historical role as a human habitat and resource, with deep connections to spirituality, shelter, and traditional practices. Today, karst landscapes are valued for cultural heritage, scientific research, and economic development through geotourism (e.g., Day, 2010; Duli et al., 2019; Khalaf, 2022). Karst environments are scientifically and educationally important because they provide a unique window into Earth's history through cave deposits and morphology, serve as natural laboratories for diverse fields like biology, geology, and hydrology, and are vital for understanding climate change. Educationally, they are used as natural classrooms for multidisciplinary learning and as a tool for local economic development through geotourism and conservation efforts (e.g., Guo and Jiang, 2011; Forti, 2015; Sulistiyowati et al., 2021). Karst geochemistry studies the chemical processes that occur when water interacts with soluble rocks, creating unique landscapes (e.g., Wang et al., 2006; Han et al., 2010; Mongelli et al., 2014; D'Angeli et al., 2017; Sracek et al., 2019; Abedini et al., 2022). It is crucial for understanding how these systems form and evolve, and for assessing the impact of pollution and climate change. A number of parameters, including the Mg/Ca ratio, can be utilized to determine historical hydrological conditions in speleothems (e.g., Cruz et al., 2007; Duan et al., 2012). The temperature-dependent Mg partitioning into speleothems is usually outweighed by the notable fluctuations in the drip-water Mg/Ca ratio (e.g., Fairchild and Treble, 2009; Duan et al., 2024). The seasonal variations in the Mg/Ca ratio are thought to be exclusively explained by temperature (e.g., Carlson et al., 2018). The Mg/Ca ratio in speleothems can also be a reasonable paleotemperature parameter, but its interpretation is complex and depends on specific cave conditions, such as stable source water chemistry and a strong temperature sensitivity of magnesium partitioning. While traditionally used for hydrological data, some recent studies have shown a strong correlation between Mg/Ca ratios and cave air temperature, particularly when source water Mg/Ca is relatively constant. Major ion chemistry, trace elements, and rare earth elements (REEs) are used to study karst aquifers by providing distinct signatures that reveal how water moves, mixes, and interacts with rocks. Major ions define the overall water chemistry, trace elements identify specific sources, and REEs offer unique patterns that act as natural tracers to reveal complex processes that simpler methods miss. This combined approach allows researchers to create accurate conceptual models of the aquifer system, assess its vulnerability, and manage its water resources more effectively (e.g., Tran et al., 2023).

Adsorbed silica in stalagmites serves as a climate proxy, with a higher Si/Ca ratio generally indicating drier conditions due to the suppression of calcium carbonate precipitation and a concentration of silica in the remaining drip water. The Si/Ca ratio in speleothems is influenced by several factors, including wind-blown silicate supply, soil weathering, rainfall dilution, and the precipitation rate of calcite. A direct correlation between high Si/Ca and high stable oxygen isotopes ($\delta 18O$) in a stalagmite can strengthen the interpretation that regional rainfall was a major control on the speleothem's silica content (e.g., Hu et al., 2005).

2. STATEMENT OF THE PROBLEM

The study's problem lies in the acute threat to the sustainability of vital groundwater resources housed within Libya's karst systems, particularly in critical areas like the Al Jabal Al Akhdar and the Benghazi plain. These systems are crucial water sources but are characterized by high vulnerability to pollution, overexploitation, and geomorphological hazards. Despite the recognized importance of these resources and the potential role of karst geochemistry in providing the necessary understanding for effective management and protection, there is a significant knowledge and implementation gap regarding the lack of advanced monitoring networks, systematic vulnerability mapping, and planned climate change adaptation strategies. This deficit severely limits Libya's ability to achieve sustainable development and fully leverage the economic potential (such as eco-tourism) inherent in these unique geological areas.

3. LITERATURE REVIEW

Karst landscapes are prominent in northeast Libya, particularly in the Al Jabal Al Akhdar region and Benghazi plain (e.g., El Amawy et al., 2010; AlShible, 2019; Abousaif et al., 2022; Zafir et al., 2025), where limestone bedrock has dissolved to form extensive networks of caves (Fig. 1a), solution cavities (Fig. 1b), collapse dolines (Fig. 1c), karren (Fig. 1d), and springs (Fig. 1e). These formations are shaped by lithology, structural tectonics, and hydrology, and include significant sites like the Ayn Zayanah system. The northwestern part of Libya is characterized by significant karst landforms, especially in the Tripolitanian pre-desert region, and includes diverse features like caves and dolines (e.g., Hunt et al., 1985). Karst in the south, where the Tibesti Mountains are located, is less detailed in available sources, but the area is generally characterized by a mountainous, arid landscape with limited hydrological information. However, many of these unique karst landscapes are now under threat from rapid urban development.

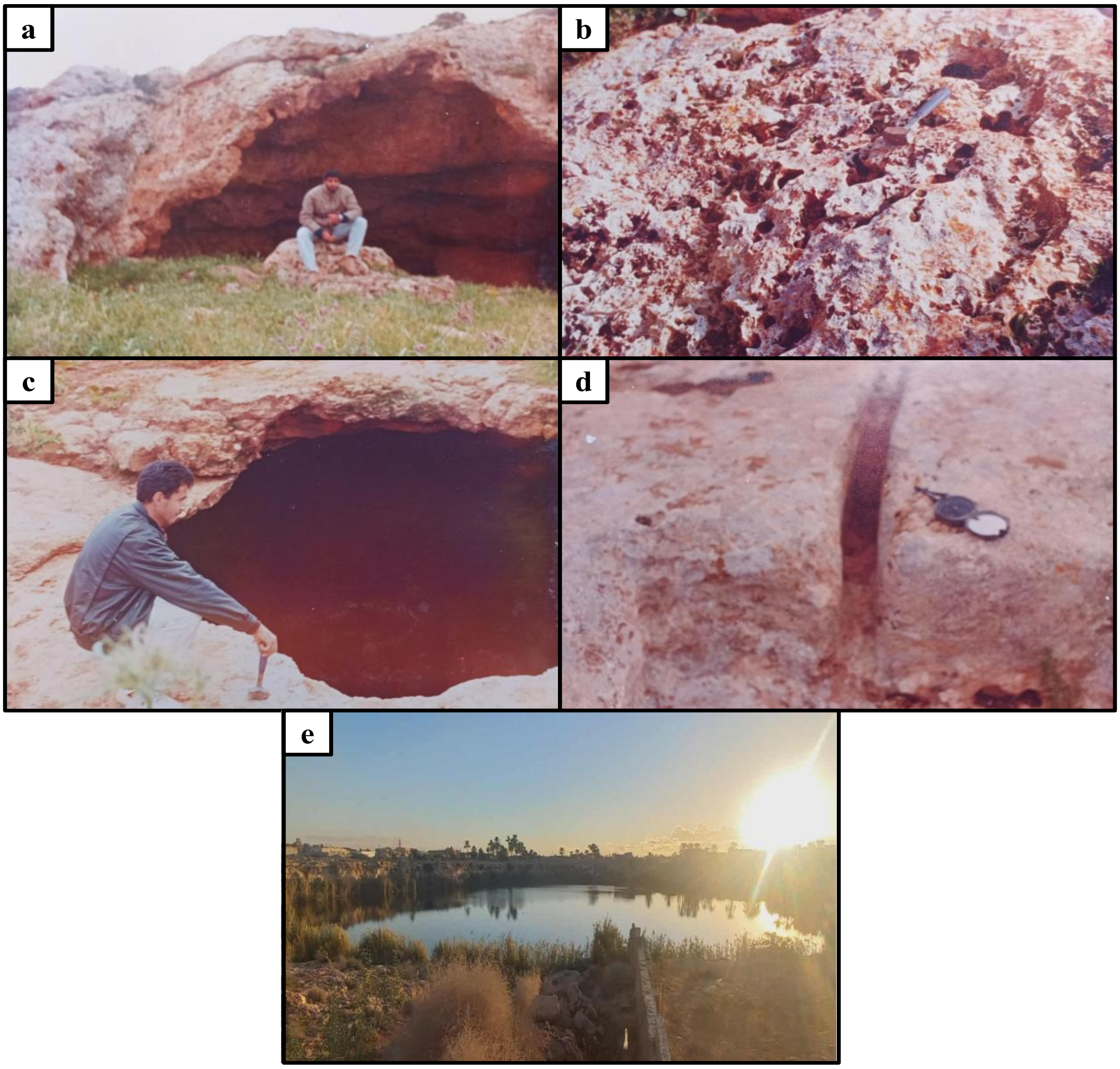

Fig. 1: Karst features in the Al Jabal Al Akhdar region ((a) Cave, (b) solution cavities, (c) collapse doline, and (d) karren) and Benghazi plain ((e) Ayn Al Majdoub Lake).

4. THE ROLE OF KARST GEOCHEMISTRY IN PROMOTING SUSTAINABLE DEVELOPMENT IN LIBYA

Libya is focusing on sustainable development through various initiatives, including the establishment of the National Development Agency (NDA) to drive strategic projects and the United Nations Development Programme (UNDP)'s partnership with the government to advance the Sustainable Development Goals (SDGs). Key efforts include improving infrastructure, supporting economic diversification beyond oil, managing water resources through the National Water Security Strategy, and developing the renewable energy sector, especially solar and wind power. Initiatives like the "Green Libya" project also aim to enhance vegetation and combat desertification.

The following considerations highlight the importance of karst geochemistry for sustainable development in Libya:

(1) Water source: Karst aquifers in Libya are a critical source of water for drinking and agriculture, although they are vulnerable to pollution and overexploitation.

(2) Geomorphological and speleogenetic understanding: Geochemical and geomorphological studies, like those conducted in Al Jabal Al Akhdar, are essential to understand how karst landscapes and caves have formed over time in response to tectonic phases and climate change.

(3) Hydrological behavior: Studying the geochemistry helps understand the flow of water through these systems, including lag times between rainfall and discharge, which is vital for sustainable management.

The challenges facing karst geochemistry in attaining sustainable development in Libya are as follows:
(1) Water quality and quantity: Karst aquifers are highly susceptible to contamination and fluctuations in water supply due to their permeable nature.
(2) Geomorphic hazards: The karst landscape can be prone to geomorphic hazards, and human activities can disrupt its stability.
(3) Ecosystem sensitivity: Karst systems host unique and sensitive ecosystems, both above ground and in caves. Activities like rerouting waterways can have significant negative impacts.
(4) Climate change: Climate change poses a threat to these aquifers, and their unique characteristics require specialized adaptation strategies.
(5) Lack of comprehensive monitoring: Many karst regions in Libya lack the robust monitoring networks needed to adequately manage water resources and prevent pollution.

The following are the pathways that karst geochemistry should promote sustainable development in Libya:
(1) Advanced monitoring: Implementing sophisticated monitoring equipment for both water quantity and quality is crucial for managing dynamic karst systems, as is the case in other Mediterranean karst aquifers.
(2) Improved management: Sustainable use requires more frequent observation of discharge and water quality and better-enlarged monitoring networks than are currently in place.
(3) Vulnerability mapping: Using tools like APLIS (altitude, pendiete/slope, lithology, infiltration, and soils) and COP (concentration of flow, overlaying layers, and precipitation) for vulnerability mapping, along with isotope analysis, can help identify areas at risk and inform protection strategies.
(4) Climate adaptation: Strategies must be developed to mitigate the negative effects of climate change on karst aquifers, including adaptation strategies.
(5) Integrated research: Continued research is necessary to build a comprehensive understanding of karst evolution and groundwater resources for better management.

5. CONCLUSIONS

Karst geochemistry is crucial for understanding vulnerable water resources and is vital for sustainable development in Libya, particularly in regions like Al-Jabal Al-Akhdar and Benghazi plain. Challenges include managing water quality and quantity in these highly permeable aquifers, addressing geomorphic hazards, and ensuring development doesn't negatively impact sensitive karst ecosystems and caves. Sustainable development requires implementing sophisticated monitoring, understanding the hydrodynamic behavior of karst systems, and adapting to climate change impacts.

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