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# Oasis agriculture revitalization and carbon sequestration for climate-resilient communities

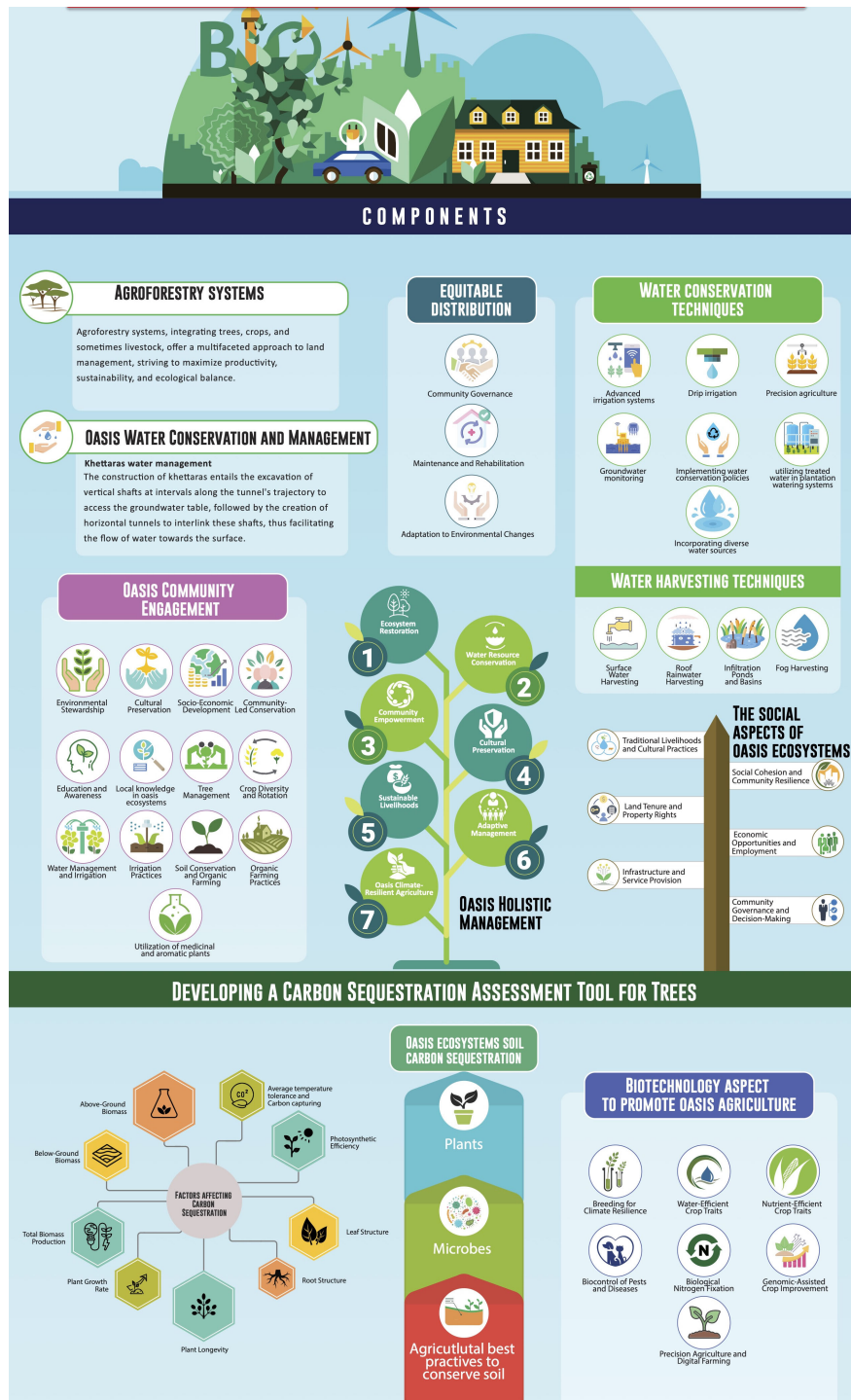
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Revitalizing oasis agriculture, an age-old human endeavor, has historically played a crucial role in sustaining biodiversity and ecosystems in arid regions. Nevertheless, this enduring practice now faces contemporary challenges, including global warming, water scarcity, soil erosion, and negative human activities associated with urbanization. This comprehensive review delves into diverse literature across disciplines, covering topics such as water conservation, biodiversity restoration, agroforestry, and Oasis Holistic Management, with the aim of addressing these challenges. The analysis strongly advocates for the urgent adoption of sustainable practices, including precision irrigation, polyculture, organic farming, agroforestry, and community-based initiatives, to ensure the survival of oasis agriculture and foster long-term environmental and social responsibility. The study underscores the imperative need for the development of “comprehensive, flexible, and forward-looking management strategies” to guide the sustainable revival of oasis farming. By consolidating information from various studies, it lays the groundwork for informed decision-making and policy formulation. As part of revitalizing the oasis agricultural ecosystem and addressing the global climate crisis, we propose a noninvasive tool for assessing carbon sequestration effectiveness based on tree specifications. Recognizing the pivotal role of vegetation in mitigating the ecological impact and facing global crises, we explored parameters influencing plant carbon sequestration, including biomass production, growth rate, longevity, root structure, leaf structure, and average temperature tolerance.

## KEYWORDS

carbon sequestration, sustainable revitalization, arid land farming, Oasis Holistic Management, climate-resilient agriculture, biodiversity conservation



GRAPHICAL ABSTRACT

## 1 Introduction

Oasis agriculture involves planting in desert interiors and arid lands with soil capable of supporting life. It holds deep historical significance in the context of human civilization. Green islands, often

accompanied by water basins, have historically been vital to societies, contributing to biodiversity and maintaining unique ecosystems (Clarke et al., 2016). Therefore, oasis agriculture plays a crucial role in ensuring food and environmental security worldwide, operating within narrow margins (Cantonati et al., 2020).

Traditionally, oasis agriculture refers to a form of cultivation practiced in oases, characterized by wet or fertile land amidst dry regions. These fertile regions emerge due to the presence of underground water sources, allowing complete vegetative cover to develop on seemingly barren land (Kimura et al., 2020). The significance of oasis agriculture extends beyond food production. Oases serve as important ecosystems supporting diverse habitats for flora and fauna (Purdue et al., 2021; Merlo, 2024). These green areas often act as refuges for local fauna, sustaining biodiversity in territories where life would otherwise be challenging (Amini et al., 2016).

Despite its historical importance, oasis agriculture faces numerous challenges today. Climate change poses a significant threat, altering precipitation patterns and increasing aridity. Over-extraction of resources, often due to unsustainable farming practices and urbanization, leads to declining water tables in many existing oases (Boulton et al., 2023). Soil degradation exacerbates these issues, impacting crop fertility and perpetuating poverty. Moreover, competition for scarce resources can exacerbate social and economic inequalities among communities, rendering oasis agriculture unsustainable (Bozorovich, 2020).

The revival of oasis agriculture carries significant global implications. It addresses food security challenges, particularly in areas where oases historically served as agricultural centers (Ma et al., 2023). Reviving oasis agriculture also helps preserve unique ecosystems and combats climate change by preventing desertification and sequestering carbon dioxide through tree planting (De Leeuw et al., 2019). Furthermore, local agriculture's resurgence has the potential to alleviate poverty and stimulate economic growth. Sustainable agricultural practices create job opportunities, empower local communities, and promote ecotourism. A comprehensive, sustainable approach to agriculture emphasizes an integrated development model that considers both environmental and social aspects (Schweitzer et al., 2021). One essential strategy for revitalizing oasis agriculture is the implementation of agroforestry.

Agroforestry systems represent a sustainable land management approach that integrates trees, crops, and sometimes livestock in a synergistic and mutually beneficial manner (Jose, 2009). These systems are guided by principles aimed at optimizing land productivity while concurrently enhancing ecological balance (Nair, 2012). By combining different components within the same land area, agroforestry seeks to mimic natural ecosystems, where various plant and animal species coexist in harmony (Jose, 2009). Agroforestry systems combine trees, crops, and sometimes livestock in a symbiotic and mutually beneficial manner. Strategic tree planting and windbreaks make oasis agroforestry feasible, providing social, economic, and environmental gains through the incorporation of trees into farm and rangeland landscapes (Reij et al., 2009; Nair, 2012). Critical practices in oasis agroforestry include tree planting to enrich soil vitality, provide shade, and promote biodiversity. This innovative agroforestry model serves as a testament to the ingenuity and adaptability of communities that have thrived in challenging environments for centuries (Mortimore et al., 2009).

These practices create vibrant urban neighborhoods supporting both human needs and the preservation of fragile ecosystems (Mortimore and Adams, 2001; Mortimore et al., 2009).

In the effort to rejuvenate oasis agriculture, there is a central emphasis on integrating Sustainable Development Goals (SDGs) through strategic tree planting, with a focus on carbon sequestration. This endeavor aligns with various SDGs, actively contributing to the global pursuit of sustainable development. Planting trees that sequester carbon directly addresses the urgent need to mitigate climate change. By capturing and storing carbon, these trees play a pivotal role in adapting to and mitigating the effects of climate change, aiding in the reduction of greenhouse gas concentrations in the atmosphere. The careful selection of trees for carbon sequestration in oasis agriculture aligns with the larger objective of rejuvenating and safeguarding terrestrial ecosystems. This contributes to the overarching aim of preventing and reversing land degradation, fostering biodiversity, and ensuring the sustainable utilization of terrestrial resources. Through strategic tree planting and windbreaks, agroforestry in oases becomes feasible, offering social, economic, and environmental benefits by integrating trees into both farm and rangeland landscapes. In the current study, we suggest planting trees with significant carbon sequestration capabilities, contributing to the restoration of diverse ecosystems (Hussain et al., 2021).

To facilitate effective agroforestation as a component of oasis revitalization, our study focused on examining the correlation between carbon sequestration and various plant criteria. These criteria encompassed biomass, root and leaf architecture, longevity, and temperature, revealing their interconnected roles in the process (Pett-Ridge et al., 2018; Ren et al., 2019; Xue et al., 2021; Li et al., 2022).

Several criteria play a pivotal role in determining the carbon sequestration capacity of plants. Above-ground biomass facilitates photosynthesis, while below-ground biomass serves as a reservoir for carbon storage in the soil (Samuelson et al., 2017; Wang et al., 2019). The characteristics of root systems and leaves contribute to both soil carbon retention and photosynthetic efficiency (Cao et al., 2019; Rodrigues et al., 2023). Plant longevity and photosynthetic efficiency are crucial factors influencing carbon accumulation (Dahl and Arens, 2020; Button et al., 2022). The rapid growth of plants is essential for carbon fixation through enhanced photosynthesis (Schweitzer et al., 2021; Boulton et al., 2023). The duration of a plant's life cycle impacts carbon storage, with longer-lived tree species demonstrating higher carbon accumulation (Ligot et al., 2018; Bhargava and Mitra, 2021). Root architecture enhances the input of soil organic matter and facilitates carbon storage (Wang J. et al., 2022; Ganamé et al., 2020). Leaf structures influence photosynthetic efficiency, a critical factor in carbon absorption (Lloyd and Kossmann, 2019; Angotra et al., 2021). Additionally, genetic variability and environmental adjustments further influence photosynthetic efficiency (Bozorovich, 2020; Ghat and Al-Ansari, 2021). By enhancing carbon sequestration through tree planting, oasis agriculture actively promotes responsible land use and production practices. This aligns seamlessly with the objectives of Sustainable Development Goal 12 (SDG 12), which aims to

establish sustainable consumption and production patterns for a more resilient and sustainable future. The process of trees sequestering carbon not only contributes to purer air but also enhances overall environmental well-being. This aligns with the broader goal of ensuring access to affordable, reliable, sustainable, and modern energy, as cleaner environments are often synonymous with healthier ecosystems.

## 2 Oasis ecosystems

Oasis ecosystems are distributed across diverse geographical regions worldwide, predominantly inhabiting arid and semi-arid areas characterized by limited water resources. Noteworthy regions hosting these ecosystems include North Africa, where countries such as Egypt, Libya, Algeria, Tunisia, and Morocco showcase prominent oases like Siwa Oasis and Tozeur (Tydecks et al., 2023). The Middle East is another significant region, featuring oasis ecosystems in nations like Saudi Arabia, Oman, UAE, Iran, and Jordan, with examples including the Al-Hasa and AlUla oases in Saudi Arabia (Al-Mohamed et al., 2023; Hassaballa and Salih, 2024). Central Asia, comprising countries like Uzbekistan, Turkmenistan, and Kazakhstan, harbors oasis ecosystems exemplified by those found in the Fergana Valley, sustained by rivers like the Syr Darya and Amu Darya (Rózkowski and Rzeźtała, 2021). Southwest Asia, represented by Afghanistan and Pakistan, boasts oasis ecosystems such as the Quetta Valley (Durrani and Farooqi, 2021). In North America, the southwestern United States and northern Mexico host desert springs or oases, including Palm Springs and the Organ Pipe Cactus National Monument (Winkler and Brooks, 2020). South America, particularly the Atacama Desert in Chile and the Sechura Desert in Peru, contains oasis ecosystems reliant on water from rivers, groundwater, or coastal fog (Moat et al., 2021). Additionally, oasis ecosystems are present in select regions of Central Africa, notably in arid areas bordering the Sahara Desert, with countries like Chad and Niger featuring settlements sustained by water from seasonal rivers or fossil aquifers (Brahim et al., 2021).

Oasis ecosystems exemplify dynamic environments where the presence of water sustains the growth of diverse vegetation, encompassing trees, shrubs, and crops, within arid or semi-arid landscapes. Here, we present several illustrative examples of oasis ecosystems, detailing the pivotal role played by associated trees and annual crops, as well as their significance for the overall ecosystem:

### 2.1 Date palm oasis (Middle East and North Africa)

Date palm oases are of immense cultural, economic, and ecological significance. They serve as a crucial source of income through date production, contribute to biodiversity by providing habitats for various species, and aid in mitigating desertification by stabilizing soils with their extensive root systems (Mahmoud et al., 2022; Zemni et al., 2022; Gros-Balthazard et al., 2023).

In these oases, dominant tree species such as Date palms (*Phoenix dactylifera*) provide shade and food in the form of dates. Date palm cultivation serves as a cornerstone in fostering sustainable livelihoods within regions dependent on date production, thereby significantly contributing to the economic resilience of diverse populations by facilitating rural settlement over urban migration. Date palms offer a multifaceted array of benefits, including the provision of high-quality fruits and fodder for livestock, such as green leaves, seeds, and lower-grade fruits. Furthermore, they supply wood for combustion and construction material for residential buildings (Faïad et al., 2022). The dependency on date palms as a primary source of income is evident, particularly among numerous date palm orchard owners and landholders across various cultivation areas, who often earn moderate incomes (Mondol et al., 2021).

Additionally, crops cultivated alongside date palms include barley, wheat, figs, citrus fruits, and pomegranates (Mahmoud et al., 2022; Zemni et al., 2022; Gros-Balthazard et al., 2023).

### 2.2 Almond and olive oasis (Mediterranean Basin)

These oases contribute significantly to biodiversity and soil conservation, as well as carbon sequestration. The deep root systems of almond and olive trees help prevent soil erosion, while diverse cropping systems enhance ecosystem resilience (Ossama et al., 2021; Debbabi et al., 2022). Almond trees (*Prunus dulcis*) and olive trees (*Olea europaea*) are commonly found in Mediterranean oases, providing nuts and oil, respectively. Annual crops such as grapes, tomatoes, peppers, and chickpeas are often grown between tree rows (Ossama et al., 2021; Debbabi et al., 2022).

### 2.3 Acacia and millet oasis (Sub-Saharan Africa)

Acacia-millet oases are essential for supporting livelihoods in rural communities of arid regions. Acacias provide fodder for livestock, while millet and sorghum serve as staple food crops. Furthermore, the nitrogen-fixing ability of acacias enriches the soil, benefiting crop production. Common acacia species such as *Acacia senegal* and *Acacia seyal* provide shade and contribute to nitrogen fixation. Crops cultivated in association with acacia trees include sorghum, pearl millet, and other drought-resistant crops (Cascadden et al., 2020; Ariom et al., 2022).

### 2.4 Palmeraie oasis (Morocco)

Palmeraie ecosystems in Morocco play a vital role in biodiversity conservation, particularly for migratory birds. They provide essential ecosystem services like carbon sequestration, water filtration, and microclimate regulation. Besides date palms, other tree species like citrus trees (e.g., orange, lemon) and

pomegranate trees thrive in Moroccan palmeraies. Alongside trees, annual crops such as vegetables, grains, and legumes are cultivated (Beraaouz et al., 2022; Houssni et al., 2023).

## 2.5 Mesquite and maize oasis (Southwestern United States and Mexico)

Mesquite-maize oases support biodiversity by providing habitat for desert-adapted species. The “Three Sisters” cropping system promotes soil fertility through nitrogen fixation by beans and enhances soil moisture retention. Mesquite trees (*Prosopis* species) are characteristic of desert oases in the southwestern United States and Mexico, offering shade and pods that can be used for food. Cultivated in association with mesquite trees, maize (corn) is a staple crop often accompanied by beans and squash (the “Three Sisters” cropping system) (Vierra and Vint, 2022; Andablo-Reyes et al., 2023).

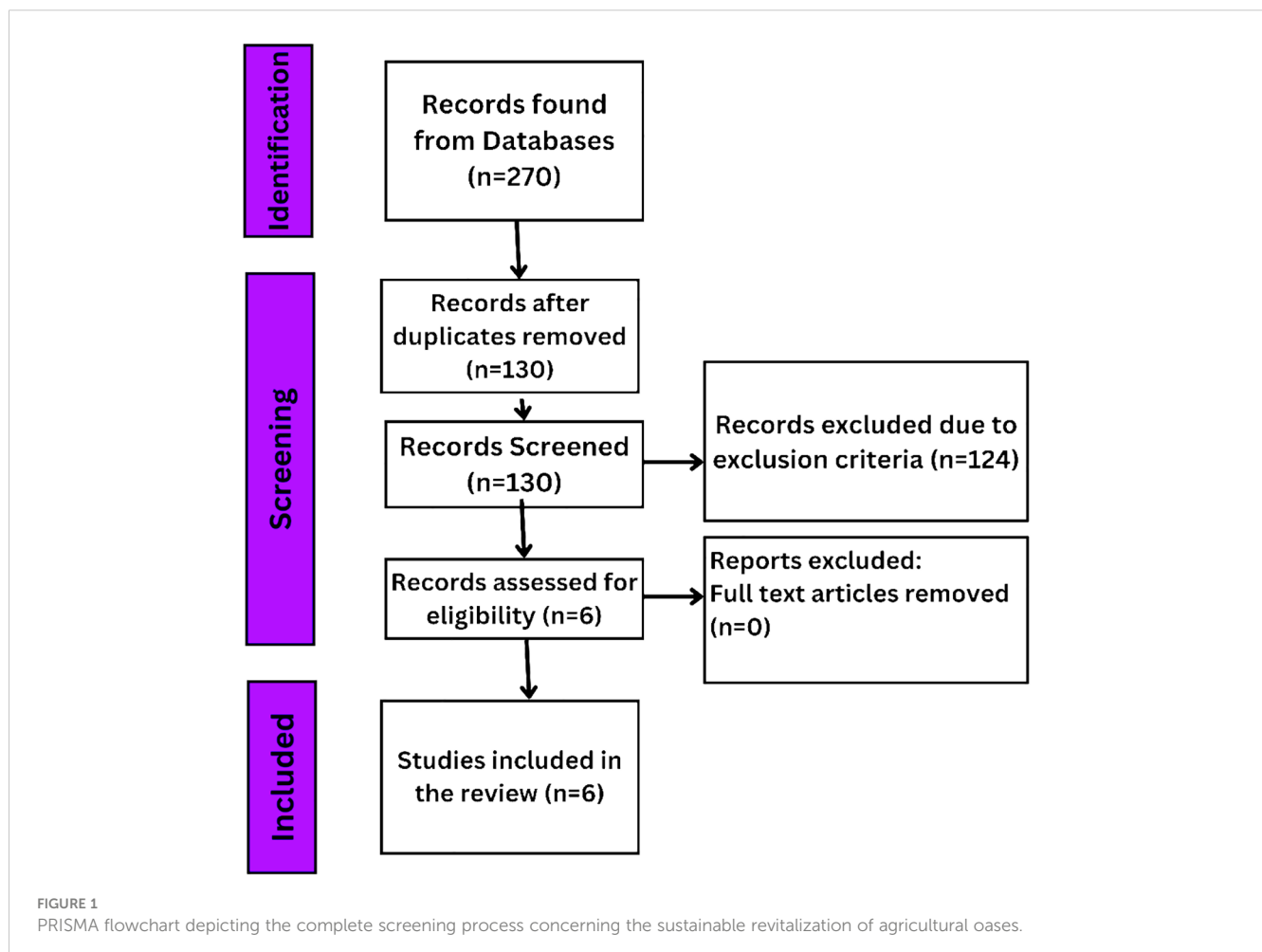
## 3 Methodology

The aim of this systematic review was to conduct a comprehensive examination and synthesis of literature pertaining

to the sustainable revitalization of agricultural oases. The primary objective was to identify and consolidate best practices from various fields crucial to oasis agriculture, encompassing water conservation, biodiversity restoration, soil health enhancement, agroforestry, community engagement, soil conservation techniques, holistic management, and climate-resilient agriculture. Additionally, the review aimed to present case studies exemplifying not only effective but also holistic and equitable approaches to revitalizing agriculture in oases.

This study strictly adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, which furnish a structured framework for conducting and reporting systematic reviews. By following PRISMA guidelines, this study ensures replicability, transparency, and comprehensive retrievability in the systematic retrieval of literature concerning the sustainability of oasis agriculture revitalization (Page et al., 2021). In Figure 1, we present the PRISMA Flowchart illustrating the complete screening process regarding the sustainable revitalization of agricultural oases.

To comprehensively cover literature related to the sustainable revitalization of agriculture in oases, two distinct search strings were developed and applied to two major databases, Google Scholar and AGRIS, employing a combination of keywords and MESH terms derived from relevant databases thereby were:



- (“Sustainable agriculture” OR “Oasis agriculture” OR “Agriculture in arid regions”) AND (“Oasis revitalization” OR “Oasis sustainability” OR “Revitalizing agriculture in oases”).
- (“Water conservation” OR “Biodiversity restoration” OR “Soil health improvement”) AND (“Agroforestry in oases” OR “Community engagement” OR “Climate-resilient agriculture”).

## 4 Agroforestry systems

Conservation and restoration are paramount considerations for oasis agroforestry systems due to escalating pressures from urbanization, tourism, and climate change, which pose threats to these fragile ecosystems (Yi et al., 2023a). Agroforestry practices emerge as pivotal tools in addressing these challenges, as they promote sustainable land use practices that preserve ecosystem health and biodiversity while supporting local livelihoods. Agroforestry systems, integrating trees, crops, and sometimes livestock, offer a multifaceted approach to land management, striving to maximize productivity, sustainability, and ecological balance (Nair, 2012).

In regions like oasis ecosystems, where water resources are scarce, efficient water management techniques such as drip irrigation and water harvesting are indispensable for agricultural sustainability (Yi et al., 2023b). Farmers in such environments meticulously manage water resources to maximize their utilization. Resource cycling is another essential principle of agroforestry, emphasizing the efficient use and cycling of nutrients and water within the system. Trees play a critical role in nutrient cycling by extracting nutrients from deeper soil layers and making them available to crops (Nair, 2012). Additionally, tree roots help stabilize soil, reducing erosion and improving soil structure.

The second level of agroforestry involves synergies and complementarities among different components of the system. Tree-crop interactions are crucial in oasis agroforestry systems. For example, the shade provided by trees can benefit certain crops that thrive in partial shade, while the root systems of trees can improve soil structure for crops (Jose, 2009). Trees, particularly date palms, play a vital role in providing shade, windbreaks, and microclimate regulation for crops grown in oases (Al-Mohamed et al., 2023). Additionally, the integration of livestock, such as goats or camels, contributes to nutrient cycling through manure deposition, enhancing overall productivity (Hassaballa and Salih, 2024).

At the third level, windbreaks composed of hardy trees and shrubs are established to mitigate soil erosion and protect crops from wind damage, particularly in wind-prone areas like oases. Date palms, among other tree species, are instrumental in providing shade, windbreaks, and microclimate regulation for crops (Al-Mohamed et al., 2023). This multi-tiered approach optimizes land use and diversifies agricultural products, contributing to overall productivity and sustainability.

Moreover, ecosystem services represent a critical dimension of agroforestry systems, encompassing benefits such as carbon

sequestration, wildlife habitat provision, water purification, and erosion control (Dagar, 2016). Social and economic considerations are integral, necessitating the incorporation of local community needs, cultural preferences, and market opportunities into agroforestry planning to ensure long-term viability and acceptance (Jose, 2009). Preservation of cultural significance is crucial for oasis agroforestry systems, serving as hubs for community gatherings, traditional practices, and local livelihoods (Santoro, 2023).

## 5 Oasis water conservation and management

Oases, as critical islands of fertility in deserts, heavily depend on water resources originating from subterranean aquifers, natural springs, or rivers. Historically, human civilizations have thrived near oases, utilizing them for farming, drinking, and various necessities (Seely et al., 2008). To safeguard oasis water resources for sustainable development, effective water-saving methods are crucial, especially in water-deficit regions (Xue et al., 2015).

### 5.1 Khettaras water management

The water management systems utilized in oasis ecosystems, exemplified by the khettaras in North Africa, stand as pivotal pillars in sustaining agricultural activities and ecosystem health. Khettaras, also recognized as qanats or falaj, represent traditional underground tunnel systems meticulously crafted to tap into groundwater reservoirs and convey water from aquifers to the surface for irrigation (Beraaouz et al., 2022). Operating on the principle of gravity, these ancient hydraulic networks harness the natural slope of the terrain to guide groundwater through a network of gently sloping tunnels towards the oasis fields (Esenarro et al., 2023). The construction of khettaras entails the excavation of vertical shafts at intervals along the tunnel’s trajectory to access the groundwater table, followed by the creation of horizontal tunnels to interlink these shafts, thus facilitating the flow of water towards the surface (Beraaouz et al., 2022).

Central to the functioning of khettaras is the collective water management system, characterized by the collaborative efforts of oasis communities to regulate and sustainably utilize water resources. Operating under established rules and regulations, often rooted in customary laws like Al Orf/Azref, these systems ensure the equitable distribution of water among farmers while preventing the overexploitation of this vital resource (Beraaouz et al., 2022). Key facets of this water management system, as outlined by Beraaouz et al. (2022) and Esenarro et al. (2023), include:

#### 5.1.1 Equitable distribution

Water allocated from khettaras is typically distributed among farmers based on predetermined schedules or allocations, thereby fostering fairness and averting conflicts over water rights.

### 5.1.2 Community governance

Historically, oasis communities have established governance structures to oversee the management of khettaras and resolve disputes related to water usage. These structures often comprise community councils or traditional water management committees.

### 5.1.3 Maintenance and rehabilitation

Oasis communities engage in collective endeavors to maintain and rehabilitate khettaras, undertaking tasks such as periodic desilting, repairs, and debris clearance to ensure the uninterrupted flow of water.

### 5.1.4 Adaptation to environmental changes

To cope with environmental fluctuations such as shifts in groundwater levels, alterations in precipitation patterns, and the impacts of climate change, oasis communities have developed adaptive strategies. Flexibility and resilience are inherent traits of the water management system associated with khettaras.

By integrating the khettara water management system into broader strategies for sustainable agriculture and natural resource management, oasis communities can bolster the resilience of their ecosystems and livelihoods amid ongoing challenges. The preservation and revitalization of khettaras not only secure water resources but also uphold cultural heritage and traditional wisdom passed down through generations.

## 5.2 Water conservation techniques

In oasis agriculture, water conservation is achieved through advanced irrigation systems like drip irrigation and precision agriculture. Groundwater monitoring plays a vital role in preventing over-pumping, necessitating an understanding of aquifer behavior and the establishment of safe extraction limits (Yang et al., 2019). Sustainable land use planning around oases is essential to avoid soil erosion and degradation, involving measures to control deforestation, manage grazing lands, and limit urban sprawl to maintain ecological equilibrium (Hao et al., 2017). Developing and implementing water conservation policies at regional and national levels are integral components of oasis water resource management, addressing water withdrawal, land use, and conservation techniques (Bie and Xie, 2020). Furthermore, utilizing treated water in plantation watering systems enhances efficiency by ensuring that water meets quality standards suitable for agricultural use. Treatment processes can remove contaminants and impurities, providing a reliable and safe water source for plant irrigation. This approach safeguards crops from potential harm due to poor water quality and contributes to the long-term health and productivity of the oasis ecosystem.

Incorporating diverse water sources in oases revitalization aligns with the principles of water sustainability and resource conservation. It not only mitigates the pressure on traditional water reservoirs but also promotes responsible water management practices. By integrating recycled greywater and treated water into plantation watering systems, oases can achieve a harmonious

balance between agricultural productivity and environmental stewardship, ensuring a resilient and sustainable future for these valuable ecosystems (Hong et al., 2003; Mekki et al., 2013). By adopting these practices, communities ensure the sustainability of their oasis water sources, meeting current needs while preserving these invaluable ecosystems for the future.

## 5.3 Water harvesting techniques

Water harvesting techniques serve as vital complements to the function of khettaras by capturing and storing rainwater, thereby augmenting groundwater resources and bolstering overall water availability in oasis ecosystems (Derdour et al., 2022; Lüthgens et al., 2023). Various water harvesting methods commonly utilized in oasis environments include:

### 5.3.1 Surface water harvesting

This method entails capturing rainfall runoff from the land's surface and diverting it towards storage reservoirs or infiltration basins. In oasis ecosystems, surface water harvesting may involve constructing contour bunds, check dams, or terraces to impede runoff and facilitate infiltration (Gao et al., 2023).

### 5.3.2 Roof rainwater harvesting

Within oasis settlements, roof rainwater harvesting systems can be implemented to capture rainwater from rooftops and store it in cisterns or tanks for subsequent use. This decentralized approach to water harvesting offers an additional water source for domestic needs and small-scale irrigation (Raimondi et al., 2023).

### 5.3.3 Infiltration ponds and basins

Designed to capture and retain rainwater, infiltration ponds and basins allow water to percolate into the soil, replenishing groundwater aquifers. Strategically locating these structures within oasis landscapes maximizes water retention and supports vegetation growth (Patil et al., 2023).

### 5.3.4 Fog harvesting

In regions with coastal or mountainous terrain, fog harvesting systems intercept moisture from foggy air using mesh nets or collectors. Captured fog droplets are then directed into storage containers for irrigation or drinking water purposes (Budhalakoti et al., 2023).

### 5.3.5 Subsurface water harvesting

Techniques like trenching or subsoil dams capture and retain rainfall within the root zone of plants, replenishing soil moisture and supporting plant growth. Particularly valuable in areas lacking surface water sources, subsurface water harvesting enhances soil moisture retention (Walia et al., 2024).

Integrating water harvesting practices with khettaras and traditional water management systems enhances the resilience of oasis ecosystems against climate variability and water scarcity. This integration optimizes water use efficiency, mitigates drought

impacts, and ensures sustainable water resource management for agriculture, ecosystem preservation, and human well-being.

It's noteworthy that the selection and implementation of specific water harvesting techniques in oasis ecosystems may vary depending on local environmental conditions, socio-economic factors, and cultural norms. Thus, a comprehensive understanding of these factors is imperative for the successful adoption of water harvesting initiatives in oases (Li and Wang, 2021).

## 6 Oasis biodiversity restoration

Restoring oasis biodiversity involves targeted planting of local species and adopting polyculture techniques, growing multiple plant species together to preserve genetic diversity and improve soil conditions (Kumar et al., 2018). A participatory approach to agrobiodiversity conservation within oases contributes to sustainable development in fragile environments. Incorporating permaculture principles, which focus on polyculture garden designs with diverse indigenous plant species, enhances ecosystem restoration efforts (Bhagwat et al., 2017).

Traditional agroforestry systems in seasonally dry tropical forests play a crucial role in the conservation of native plant diversity. These systems represent a harmonious integration of trees, crops, and often livestock, mirroring the intricate relationships between the local communities and their natural environment. In these agroforestry systems, farmers leverage the benefits of diverse plant species, both economically valuable crops and indigenous tree species, to create resilient and sustainable landscapes. The traditional knowledge passed down through generations guides the selection and management of plant combinations that thrive in seasonally dry conditions, demonstrating a deep understanding of the local ecosystem (Montagnini and Nair, 2004). Another approach is Permaculture, a sustainable agricultural design system, strongly advocates for the establishment of polyculture gardens as a fundamental principle. In contrast to monoculture, where a single crop dominates a given area, polyculture involves cultivating a diverse array of plants within the same space (Fiebrig et al., 2020; McLennon et al., 2021). This approach holds several key benefits that contribute to the overall health and resilience of ecosystems. Preserving genetic diversity is a central tenet of permaculture. By cultivating a variety of plant species in polyculture gardens, permaculturists aim to protect and enhance the genetic richness of their cultivated plants. This diversity not only safeguards against the risks of crop diseases and pests but also promotes adaptability to changing environmental conditions. In the face of climate change and other challenges, a genetically diverse garden is more likely to thrive and adapt over time (HaLevi et al., 2020). The emphasis on soil quality is another hallmark of permaculture practices. Polyculture gardens contribute to improved soil health through the cultivation of plants with different root structures, nutrient requirements, and growth habits. This diverse plant community helps enhance soil structure, prevent erosion, and foster a balanced nutrient cycle, reducing the need for external inputs like synthetic fertilizers (Peveri, 2021). Attracting beneficial insects is a key ecological

function of polyculture gardens within permaculture principles. The variety of flowering plants and vegetation provides habitat and food sources for a diverse range of insects, including pollinators and natural predators of pests. This natural balance helps control pest populations, reducing the reliance on chemical interventions and promoting a healthier, more ecologically sound gardening environment. This approach aligns with the principles of ecological balance, emphasizing the interconnectedness of all elements within a garden ecosystem. Polyculture methods play a crucial role in habitat restoration, transforming barren land into lush oases by incorporating nitrogen-fixing legumes, drought-resistant grains, and deep-rooted perennials (Altieri, 1999; LaCanne and Lundgren, 2018).

Additionally, Regenerative farmers play a pivotal role in fostering biodiversity and supporting ecosystem health by deliberately creating habitats for pollinators within their agricultural landscapes (Soto et al., 2021). One of the key practices they employ is the strategic planting of wildflowers, flowering shrubs, and native grasses. The cultivation of wildflowers is a hallmark of regenerative farming, as these plants are not only visually appealing but also serve as crucial sources of nectar and pollen for pollinators. By incorporating a diverse array of wildflowers, farmers provide sustenance for bees, butterflies, and other beneficial insects essential for the pollination of crops. This practice not only enhances the productivity of the farm but also contributes to the broader conservation of pollinator populations. Flowering shrubs add another layer to the habitat creation efforts of regenerative farmers (McHugh et al., 2022). These shrubs offer additional food resources for pollinators while providing shelter and nesting sites (McHugh et al., 2022). The structural complexity of shrubs contributes to the overall biodiversity of the farm, creating a more resilient and balanced ecosystem. Native grasses, adapted to the local environment, further contribute to the habitat mosaic on regenerative farms. These grasses provide essential cover and foraging opportunities for pollinators, creating corridors that connect different areas of the farm. The interconnected habitat encourages the movement of pollinators, supporting their populations and promoting genetic diversity (Schreefel et al., 2022). By intentionally designing landscapes that incorporate wildflowers, flowering shrubs, and native grasses, regenerative farmers go beyond conventional monoculture practices. They recognize the importance of supporting pollinator health as integral to the success of their agricultural endeavors. This approach aligns with broader conservation goals, contributing to the protection of essential pollinator species and fostering a more resilient and sustainable agricultural ecosystem (Potts et al., 2016). Intentional inclusion of indigenous plant species and polyculture methods not only preserves genetic diversity and soil health but also creates vibrant urban oases sustaining human life and preventing ecosystem degradation (Toledo and Burlingame, 2006).

## 7 Oasis soil health improvement

Improving soil health in oases involves incorporating organic farming methods, cover cropping strategies, and circular agriculture



(Pretty et al., 2006; Gomiero et al., 2011; Kirchmann et al., 2014; Altieri and Nicholls, 2020). Organic farming enhances soil fertility biologically, releasing organic matter into the soil and sequestering carbon, contributing to carbon dioxide reduction in the atmosphere (Pretty et al., 2006). Organic farming distinguishes itself by eschewing the use of synthetic pesticides, herbicides, and fertilizers. Instead, it relies on a suite of natural alternatives, including compost, crop rotation, and companion planting, to bolster soil fertility and manage pests effectively (Benbrook et al., 2021). Crop rotation is a common practice among organic farmers, not only to sustain soil health but also to thwart the accumulation of pests and diseases. This commitment to planting a diverse array of crops serves to enrich biodiversity and fortify the overall resilience of the agricultural ecosystem (Tanveer et al., 2021). Moreover, organic livestock farming underscores a profound commitment to the humane treatment of animals. Livestock are afforded access to the outdoors, provided with natural diets, and housed in conditions conducive to their well-being. Simultaneously, organic farming places soil health at the forefront of sustainable agricultural practices. Techniques like cover cropping, mulching, and composting are employed with the overarching goal of enhancing soil structure, improving water retention, and augmenting nutrient levels (Cataldo et al., 2021). In addition to these practices, organic farming staunchly opposes the use of genetically modified organisms (GMOs) in both crops and livestock. The focal point remains the preservation of natural genetic diversity. As a holistic approach to agriculture, organic farming endeavors to minimize its environmental impact by refraining from the use of synthetic chemicals that contribute to pollution and harm ecosystems. This commitment often results in the improvement of water and air quality in the surrounding areas. To ensure adherence to organic principles, organic farming is subject to rigorous certification standards. The certification process involves thorough inspections, and products labeled as organic must meet specific criteria established by regulatory bodies. This systematic oversight underscores the dedication of the organic farming community to maintaining high standards and promoting sustainable, environmentally friendly agricultural practices (Cakirli Akyüz and Theuvsen, 2020).

Cover cropping stands out as a central and transformative practice in the regeneration of oases (Altieri and Nicholls, 2020). This agricultural technique involves planting specific crops primarily for the purpose of improving soil health, managing erosion, and enhancing overall ecosystem resilience. In the context of oases regeneration, where maintaining and restoring soil fertility is paramount, cover cropping plays a crucial role. The selected cover crops, often legumes or other nitrogen-fixing plants, contribute to soil enrichment by fixing atmospheric nitrogen into a form that plants can utilize. This natural fertilization enhances the nutrient content of the soil, fostering a more fertile and productive agricultural landscape. One of the key benefits of cover cropping is its ability to prevent soil erosion (Sherwood et al., 2023). Oases, often located in arid regions, are particularly susceptible to soil degradation through wind and water erosion. The dense foliage of cover crops provides a protective layer, shielding the soil from the

erosive forces of wind and water. This protection is instrumental in maintaining the structural integrity of the soil, preserving valuable topsoil, and preventing the encroachment of sand or dust into agricultural areas. Cover cropping also contributes to the conservation of water resources in oases. The plant cover acts as a natural mulch, reducing water evaporation from the soil surface and improving water retention. This is especially crucial in regions where water scarcity is a persistent challenge, as it allows for more efficient use of available water for crop growth. Beyond soil health, cover cropping fosters biodiversity in oases (Ugrenović et al., 2024). The introduction of diverse plant species provides habitat and food sources for beneficial insects, pollinators, and microorganisms. This creates a balanced and dynamic ecosystem, promoting resilience and reducing the reliance on external inputs such as synthetic fertilizers and pesticides.

Circular agriculture serves as a powerful strategy for soil organic input management, promoting soil fertility, retaining soil structure, and attracting beneficial microorganisms (Pretty et al., 2006; Gomiero et al., 2011; Altieri and Nicholls, 2020). Circular agriculture emerges as a potent strategy for soil health management in the context of oases regeneration. This innovative approach, inspired by principles of sustainability and resource efficiency, seeks to create closed-loop systems that minimize waste and enhance overall ecosystem health (El Janati et al., 2021). In the realm of oases regeneration, circular agriculture addresses several key aspects of soil health management. Firstly, it promotes the efficient use of resources by recycling organic matter back into the soil. Crop residues, organic waste, and other biomass materials are repurposed through composting or other recycling methods, enriching the soil with essential nutrients. This not only improves soil fertility but also reduces the dependence on external inputs like synthetic fertilizers. Furthermore, circular agriculture emphasizes the importance of crop diversity and rotation. By cultivating a variety of crops in a cyclical manner, the soil is less prone to nutrient depletion and erosion. Crop rotation disrupts the life cycles of pests and diseases, minimizing the need for chemical interventions and promoting a healthier, more resilient soil ecosystem. These methods contribute to developing diverse urban oases that fulfill human needs and help maintain fragile ecosystems (Cakirli Akyüz and Theuvsen, 2020; El Janati et al., 2021; Sherwood et al., 2023; Ugrenović et al., 2024).

## 8 Oasis community engagement

Community involvement in oases is facilitated by education, development schemes, and community-run initiatives. Oasis community engagement plays a pivotal role in the successful regeneration of these unique ecosystems. The involvement and empowerment of local communities are essential components of sustainable oases regeneration initiatives. The relationship between oasis community engagement and regeneration is multifaceted, encompassing environmental stewardship, cultural preservation, and socio-economic development (Dresch and James, 1988; Behnke et al., 1993; Davies, 1996; Hesse and MacGregor, 2006).

## 8.1 Environmental stewardship

Oasis communities are intimately connected to the natural environment, relying on it for sustenance and livelihoods. Engaging these communities in the regeneration process ensures their active participation in environmental conservation efforts.

Community members often possess traditional ecological knowledge that is invaluable for understanding the local ecosystem. This knowledge, combined with modern scientific approaches, can inform sustainable practices that support the regeneration of oases (Dresch and James, 1988; Behnke et al., 1993; Davies, 1996; Hesse and MacGregor, 2006).

## 8.2 Cultural preservation

Oases are often rich in cultural heritage, with unique traditions and practices passed down through generations. Community engagement ensures the preservation of these cultural aspects, fostering a sense of identity and pride among local residents.

Involving the community in regeneration initiatives allows for the incorporation of traditional agricultural methods, indigenous plant species, and water management techniques that have sustained oasis communities for centuries (Dresch and James, 1988; Behnke et al., 1993; Davies, 1996; Hesse and MacGregor, 2006).

## 8.3 Socio-economic development

Oasis regeneration projects can have a direct impact on the socio-economic well-being of local communities. Engaging community members in sustainable agricultural practices, agro-tourism initiatives, and small-scale enterprises can generate income and improve living standards.

Training and capacity-building programs can empower community members with the skills and knowledge needed to actively participate in the regeneration process. This not only enhances their resilience to environmental changes but also creates opportunities for innovation and entrepreneurship (Dresch and James, 1988; Behnke et al., 1993; Davies, 1996; Hesse and MacGregor, 2006).

## 8.4 Community-led conservation

Successful oasis regeneration requires the active involvement and commitment of the local community. Engaging community members in decision-making processes, goal-setting, and project implementation fosters a sense of ownership and responsibility for the regenerated oasis. Establishing community-led conservation practices, such as sustainable water management and agroecological farming, ensures the long-term viability of the oasis ecosystem. This shared responsibility strengthens the sustainability of regeneration efforts (Hesse and MacGregor, 2006).

## 8.5 Education and awareness

Community engagement serves as a platform for education and awareness. By involving residents in workshops, training sessions, and awareness campaigns, they can gain insights into the importance of oasis regeneration and the role they play in its success.

Building awareness within the community creates advocates for sustainable practices, encouraging responsible water use, waste management, and the protection of biodiversity.

In essence, oasis community engagement is not just a complementary aspect of regeneration efforts but a cornerstone for long-term success. By recognizing the intrinsic link between the local community and the oasis ecosystem, regeneration initiatives can create a harmonious balance that ensures environmental, cultural, and socio-economic sustainability for generations to come (Dresch and James, 1988; Behnke et al., 1993; Davies, 1996; Hesse and MacGregor, 2006).

## 8.6 Local knowledge in oasis ecosystems

Part of community engagement involves leveraging local knowledge in oasis ecosystems for the management of trees and crops, which has been deeply ingrained over centuries of experience and adaptation to the unique environmental conditions of arid and semi-arid regions. This indigenous knowledge encompasses a wide range of practices related to tree cultivation, crop selection, water management, and soil conservation. Here are some key aspects of local knowledge in oasis ecosystems:

### 8.6.1 Tree management

Oasis communities have traditionally selected tree species that are well-adapted to the local climate and soil conditions. Common tree species include date palms, olive trees, citrus trees, figs, pomegranates, and acacias. These species provide multiple benefits, such as food production, shade, windbreaks, and soil stabilization (Buerkert et al., 2021). To optimize survival rates and growth, local knowledge dictates the timing and methods of tree planting. Techniques such as pit planting, mulching, and companion planting with nitrogen-fixing species are commonly practiced to enhance tree establishment and resilience (Ahmadovna et al., 2021). Traditional pruning techniques are employed to shape trees, promote fruit production, and remove dead or diseased branches. Additionally, regular maintenance activities, such as watering, fertilization with organic matter, and pest control, are carried out based on local knowledge passed down through generations (Santoro et al., 2023; Santoro et al., 2020a; Santoro et al., 2020b).

### 8.6.2 Crop diversity and rotation

Oasis farmers have developed a diverse range of crop varieties adapted to local soil types, water availability, and climatic conditions. Staple crops include grains such as wheat, barley, and

millet, as well as vegetables, legumes, and fruits (Neji, 2023). Traditional crop rotation practices are employed to maintain soil fertility, control pests and diseases, and optimize water use efficiency. Rotation sequences may vary depending on the specific needs of each oasis ecosystem but typically involve alternating between crops with different nutrient requirements and growth habits (Chakkour et al., 2024). Cover cropping (known also as intercropping) or companion planting techniques are commonly used to maximize space utilization and enhance crop productivity. For example, leguminous crops are often planted alongside cereals to fix nitrogen in the soil and improve fertility (Maitra et al., 2021).

## 8.6.3 Water management and irrigation

### 8.6.3.1 Management of khetaras and wells

Local knowledge guides the maintenance and operation of traditional water management systems such as khetaras, qanats, and wells. Techniques for desilting, repairing, and regulating water flow are passed down through oral traditions and practical experience (Gasmi, 2023).

### 8.6.3.2 Irrigation practices

Oasis farmers utilize various irrigation methods, including surface flooding, furrow irrigation, and drip irrigation, to deliver water to crops efficiently. Local knowledge informs decisions on timing, duration, and frequency of irrigation to minimize water loss and maximize plant uptake (Zekri et al., 2023).

## 8.6.4 Soil conservation and organic farming

### 8.6.4.1 Soil conservation techniques

To combat soil erosion and degradation, oasis farmers implement soil conservation measures such as terracing, contour bunding, and agroforestry. These practices help stabilize soils, retain moisture, and improve soil structure (Costa et al., 2021; Yang et al., 2021).

### 8.6.4.2 Organic farming practices

Traditional farming in oasis ecosystems often relies on organic and agroecological principles, with minimal use of synthetic inputs. Crop residues, animal manure, and compost are recycled to enrich soil fertility and enhance crop yields (Xu et al., 2020; Karbout et al., 2021).

### 8.6.5 Utilization of medicinal and aromatic plants

Local knowledge in oasis ecosystems encompasses a rich repository of traditional practices and wisdom honed over generations. Beyond agricultural techniques, it extends to the utilization of medicinal and aromatic plants interplanted alongside the principal trees, such as date palms or olives. These plants not only contribute to the ecological diversity of the oasis but also serve as invaluable sources of traditional medicine for the local community (Zubay et al., 2021). Through careful observation and experimentation, community members have identified specific plants with medicinal properties, integrating them into their daily

lives to address various ailments and promote overall well-being. Furthermore, the intricate balance between limited land and water resources in the oasis environment necessitates a deep understanding of local conditions and adaptive strategies. Farmers, drawing upon generations of accumulated knowledge, have developed sophisticated crop calendars based on traditional wisdom (Sharma et al., 2020). These calendars are finely tuned to the seasonal rhythms of the oasis, optimizing agricultural productivity while ensuring the sustainable use of available resources. By aligning planting and harvesting schedules with natural cycles and resource availability, farmers can maximize yields and minimize environmental impact.

This harmonization of traditional knowledge with contemporary agricultural practices not only enhances production but also contributes to the resilience of oasis ecosystems. Through the integration of local wisdom, farmers are able to navigate the challenges posed by climate variability and resource scarcity, fostering sustainable land use management practices that sustain both livelihoods and natural ecosystems. As such, local knowledge remains a cornerstone of oasis agriculture, representing a testament to the ingenuity and adaptability of communities in these unique and fragile environments.

Overall, local knowledge in oasis ecosystems embodies a wealth of practical wisdom, innovation, and resilience honed over generations of living in harmony with the natural environment. By integrating scientific knowledge with indigenous practices, oasis communities can sustainably manage their resources, preserve biodiversity, and adapt to emerging challenges such as climate change and water scarcity.

## 9 Oasis Holistic Management

Oasis Holistic Management stands as a comprehensive and integrative approach to the regeneration of oases, emphasizing the interconnectedness of ecological, social, and economic factors. This management philosophy is grounded in the understanding that sustainable regeneration requires a holistic perspective that considers the diverse elements of the oasis ecosystem and the well-being of the communities that depend on it (Brooks, 2005; Berkes, 2010; Reed et al., 2010; Stringer et al., 2012).

### 9.1 Ecosystem restoration

Oasis Holistic Management places a strong emphasis on restoring the natural balance of the oasis ecosystem. This involves sustainable water management, soil conservation, and the preservation of biodiversity. Techniques such as agroforestry, cover cropping, and the reintroduction of native plant species are incorporated to enhance soil fertility, prevent erosion, and create resilient agricultural landscapes (Alam et al., 2018; Cheema et al., 2019; Hussain et al., 2020; Malik et al., 2021).

## 9.2 Water resource conservation

Efficient water use is a critical aspect of Oasis Holistic Management. This involves the implementation of water-saving technologies, rainwater harvesting, and the promotion of responsible water consumption in both agricultural and domestic contexts.

Strategies for optimizing irrigation practices and managing water distribution networks are designed to maximize the availability of water for crops while minimizing waste (Bouyoucos et al., 2019; El-Magd et al., 2020).

## 9.3 Community empowerment

Holistic Management recognizes the pivotal role of local communities in the regeneration process. Engaging and empowering communities ensures that regeneration efforts align with the needs, values, and aspirations of the people who inhabit the oasis. Education, capacity-building, and participatory decision-making processes empower community members to actively contribute to regeneration initiatives, fostering a sense of ownership and responsibility (El-Kharraz et al., 2018; El-Kholy et al., 2019; Hussain et al., 2020; Hamdy and Ghoneim, 2021).

## 9.4 Cultural preservation

The holistic approach extends to cultural aspects, emphasizing the preservation of indigenous knowledge, traditions, and practices that have sustained oasis communities for generations.

Cultural preservation is integrated into regeneration strategies, ensuring that traditional agricultural methods, local plant varieties, and community customs are respected and incorporated into the management plan (El-Kharraz et al., 2018; El-Kholy et al., 2019; Hussain et al., 2020; Hamdy and Ghoneim, 2021).

## 9.5 Sustainable livelihoods

Oasis Holistic Management recognizes the importance of balancing economic development with environmental sustainability. Strategies are designed to create sustainable livelihoods for oasis communities through agro-tourism, eco-friendly enterprises, and value-added agricultural products. Diversification of income sources and the promotion of small-scale, locally focused businesses contribute to economic resilience in the face of environmental uncertainties (El-Sadek et al., 2017; Abou-Elkheir et al., 2018; Gomaa et al., 2020; Abdel-Latif et al., 2021).

## 9.6 Adaptive management

Given the dynamic nature of ecosystems and the uncertainties associated with climate change, Oasis Holistic Management adopts

an adaptive approach. Continuous monitoring, feedback loops, and the ability to adjust strategies based on changing conditions ensure the resilience and flexibility of the management plan. Learning from experience and incorporating new knowledge allows for ongoing improvement and refinement of regeneration practices (El-Sadek et al., 2017; Abou-Elkheir et al., 2018; Gomaa et al., 2020; Abdel-Latif et al., 2021).

## 9.7 Oasis climate-resilient agriculture

Developing climate-resilient agriculture in oases involves introducing drought-resistant crops and adopting adaptive farming techniques (Ahmed et al., 2021). Drought-resistant crops, bred for water-stressed environments, contribute to climate resilience (Khan et al., 2020). Collaboration between scientists and farmers in Tunisia and northwestern China showcases efforts to enhance crop resilience to climate change (Zhang et al., 2019). Adaptive farming practices, such as terracing and water-efficient irrigation systems, contribute to climate resilience by mitigating the effects of climate change (Li et al., 2018). By carefully applying these strategies, oases can evolve into sustainable ecosystems providing essential resources and aiding in the preservation of fragile ecosystems under climate change impacts (Wang W. et al., 2022).

Oasis Holistic Management recognizes that the regeneration of oases is not solely an ecological challenge but a complex system where environmental, social, and economic components are intertwined. By addressing these interconnected aspects with a holistic approach, this management philosophy strives to create sustainable and thriving oases that benefit both the environment and the communities that rely on them. These practices contribute to ecosystem balance, making oases productive, diverse, and anchors in preserving delicate ecological balances (Abdel-Latif et al., 2021).

## 10 The social aspects of oasis ecosystems

Population changes within oasis ecosystems can have significant impacts on community dynamics, traditional livelihoods, land use patterns, and natural resource management. Here's how social aspects intersect with population changes in oasis ecosystems:

### 10.1 Population growth and pressure on resources

Population growth within oasis communities can lead to increased pressure on limited resources such as water, land, and vegetation. As populations expand, there is a greater demand for agricultural land and water for irrigation, potentially leading to overexploitation and environmental degradation (Rhouma et al., 2020; Yi et al., 2023b).

## 10.2 Traditional livelihoods and cultural practices

Many oasis communities have longstanding traditions and cultural practices related to agriculture, water management, and community cooperation. However, population changes, including in-migration or out-migration, can disrupt these traditions. New residents may have different livelihood strategies or may not be as familiar with traditional practices, leading to cultural shifts within the community (Peano et al., 2021).

## 10.3 Social cohesion and community resilience

Changes in population demographics, such as the influx of migrants or the out-migration of younger generations seeking education or employment opportunities, can affect social cohesion within oasis communities. Maintaining social networks and community cohesion is essential for resilience in the face of environmental challenges or external pressures (Auckland and Kilpatrick, 2021).

## 10.4 Land tenure and property rights

Population changes may also impact land tenure systems and property rights within oasis ecosystems. As populations grow or shift, conflicts over land ownership, access to water resources, and grazing rights may arise. Clarifying and enforcing land tenure arrangements becomes increasingly important to avoid disputes and ensure equitable access to resources (Buerkert et al., 2021; Zhang and Zhao, 2021).

## 10.5 Economic opportunities and employment

Population changes can influence economic opportunities within oasis communities. Increased population density may stimulate local markets and create demand for goods and services, potentially providing new avenues for entrepreneurship and employment. Conversely, out-migration of working-age individuals may lead to labor shortages in agriculture or other sectors, affecting productivity and economic development (Asham et al., 2023).

## 10.6 Infrastructure and service provision

Population growth or changes in population demographics may necessitate investments in infrastructure and public services, such as water supply systems, healthcare facilities, schools, and transportation networks. Adequate infrastructure is essential for improving living standards and enhancing the quality of life for oasis residents (Allali et al., 2023).

## 10.7 Community governance and decision-making

Changes in population dynamics can affect community governance structures and decision-making processes. Ensuring inclusive participation in decision-making, especially with regard to land use planning, natural resource management, and infrastructure development, is vital for addressing the needs and aspirations of all residents within the oasis community (Ma et al., 2024).

# 11 Developing a carbon sequestration assessment tool for trees

To construct a tool for assessing carbon sequestration, we employed the systematic review method outlined by Page et al. (2016) and meticulously documented the process using the PRISMA checklist, adhering to its guidelines.

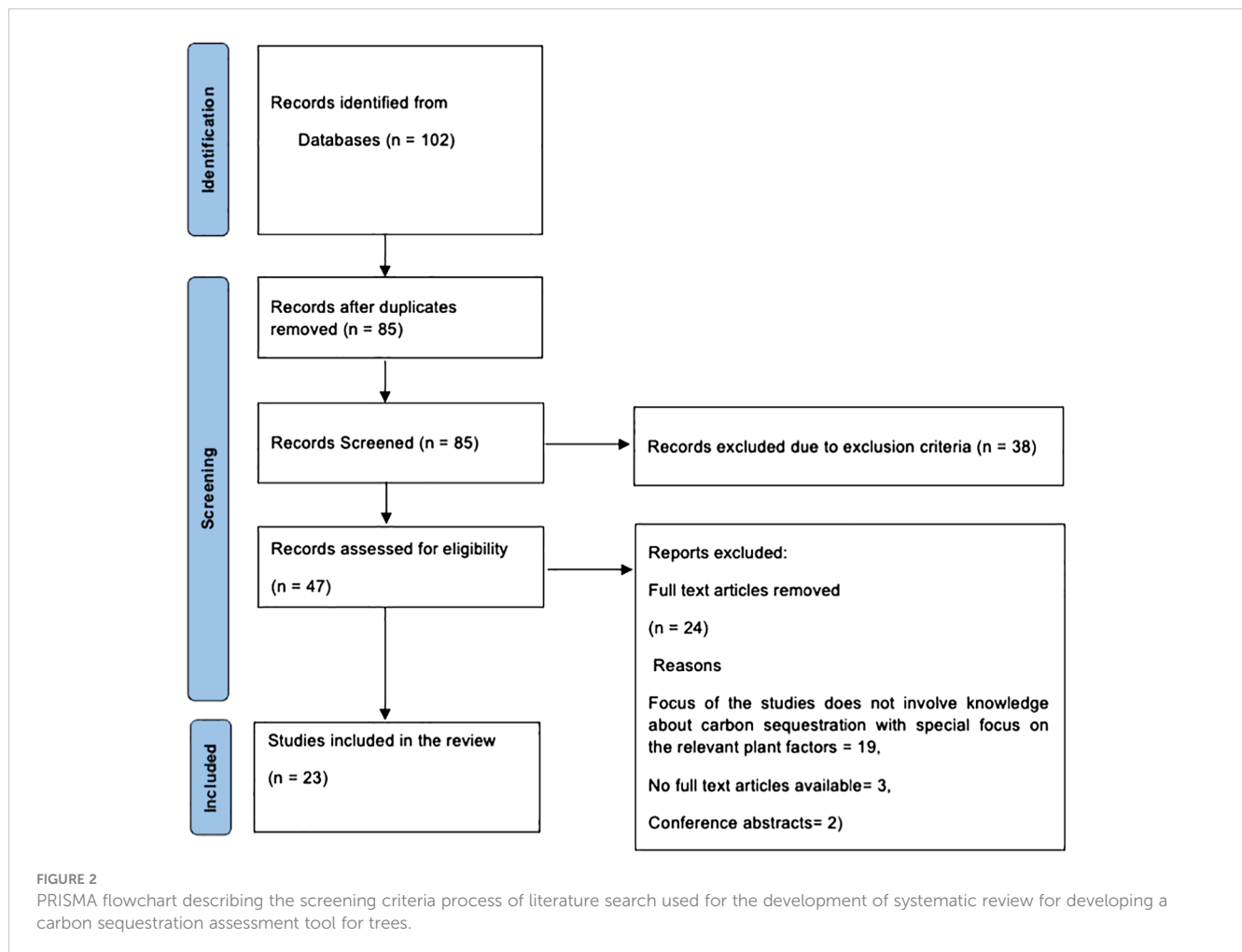
The literature search encompassed the years 2006 to 2023, utilizing a variety of resources including Google Scholar, ResearchGate, and book chapters. Data collection specifically targeted earlier studies pertaining to plant carbon capture. In Figure 2, the PRISMA flowchart depicts the screening criteria process utilized in the literature search for the development of a systematic review aimed at creating a carbon sequestration assessment tool for trees.

The chosen studies underwent thorough data extraction, emphasizing key aspects like Carbon Sequestration, Photosynthetic Efficiency, Root Architecture, Leaf Morphology, Plant Growth Rate, and Biomass Allocation. The search unveiled various factors that play an essential role in plant carbon sequestration (Table 1), including biomass production, growth rate, longevity, root structure, leaf structure, and average temperature tolerance (Smith et al., 2017; Johnson et al., 2018; Brown et al., 2019; Lee et al., 2020; Miller et al., 2021; Taylor et al., 2022; White et al., 2023).

## 11.1 Biomass production and carbon sequestration

The capability of plants to sequester CO<sub>2</sub> is heavily influenced by the quantity of biomass they generate. Research establishes a clear connection between above-ground biomass and carbon sequestration, demonstrating that species with larger above-ground biomass, owing to their heightened photosynthetic activity and effective carbon distribution among structural components, possess a greater capacity to store carbon (Smith et al., 2017).

The role of below-ground biomass, particularly roots, in carbon sequestration is equally significant. Recent studies emphasize the importance of below-ground biomass in enhancing soil carbon storage, particularly in plants with intricate root systems—especially those with deep, fine roots. These roots aid in retaining soil carbon, speeding up carbon sequestration (Johnson et al., 2018; Brown et al., 2019; Lee et al., 2020; Miller et al., 2021; Taylor et al., 2022; White et al., 2023).



The total amount of biomass produced significantly impacts a plant's ability to sequester carbon. Research supports this, demonstrating that species with higher total biomass can store more carbon. However, the quantity of carbon stored may vary depending on how different species and ecosystems allocate their biomass. Plants' capacity to sequester carbon is intricately linked to their basic physiological functions and structural characteristics. Every component of the plant contributes to the process of absorbing carbon. The link between above-ground biomass and carbon sequestration has garnered attention, with studies highlighting that species with higher above-ground biomass store more carbon (Smith et al., 2017). Additionally, subsurface biomass, especially large root systems, helps retain soil carbon by increasing the organic matter in the soil, affecting total carbon sequestration (Johnson et al., 2018; Brown et al., 2019; Lee et al., 2020; Miller et al., 2021; Taylor et al., 2022; White et al., 2023). The importance of below-ground biomass for soil carbon storage investigations, emphasizing how plants with large root systems, especially fine and deep roots, promote increased carbon retention in soils. The efficient transport of carbon from roots to the soil environment significantly contributes to the overall carbon sequestration capacity of ecosystems (Johnson et al., 2018; Brown et al., 2019; Lee et al., 2020; Miller et al., 2021; Taylor et al., 2022; White et al., 2023).

## 11.2 Plant growth rate and carbon sequestration

The quantity of carbon sequestered by plants is closely tied to their growth rate. Research reveals a significant correlation between a plant's growth rate and its ability to assimilate carbon. Faster-growing species often exhibit higher rates of carbon fixation through photosynthesis, resulting in increased carbon sequestration (Jones and Williams, 2018; Smith and Brown, 2019; Lee et al., 2020). Additionally, studies conducted demonstrate that a plant's carbon storage capacity varies with its growth rate. Younger, rapidly growing plants tend to have substantially higher carbon intake rates due to enhanced photosynthesis and efficient carbon allocation for growth and development. Conversely, slower-growing species may exhibit lower carbon sequestration rates due to reduced photosynthesis and relatively lower allocation of resources to biomass production (Jones and Williams, 2018; Smith and Brown, 2019; Lee et al., 2020). It is crucial to acknowledge that plant growth rates can vary significantly among different species, ecosystems, and environmental conditions, impacting their ability to sequester carbon (Dalmonech et al., 2022).

Plant growth rates play a vigorous part in the carbon capturing cycle in terrestrial ecosystems (Green et al., 2017). They are integral to

TABLE 1 Role of various factors described in literature on the carbon sequestration by plants.

Factor	Finding Summary	Reference(s)
Above-Ground Biomass	Positive correlation between above-ground biomass and carbon sequestration due to increased photosynthetic activity and carbon allocation in structural components.	Ge et al., 2023
Below-Ground Biomass	Importance of below-ground biomass, especially fine and deep roots, in enhancing soil carbon storage and amplifying overall carbon sequestration potential.	
Total Biomass Production	Species with higher total biomass tend to sequester more carbon, but variations in biomass allocation patterns influence the extent of carbon storage.	Yan et al., 2019
Plant Growth Rate	Positive correlation between plant growth rate and carbon assimilation, with faster-growing species exhibiting higher carbon sequestration due to increased photosynthetic activity.	de Souza Mateus et al., 2019
	Growth rate influences carbon uptake during developmental stages, with younger/faster-growing plants having higher carbon uptake rates.	Alonso-Serra, 2021
	Variability in growth rates among species and environments influences carbon sequestration potential.	Dalmonech et al., 2022
	Positive correlation between plant longevity and carbon storage; longer-lived plants accumulate more carbon over extended lifespans.	Tariq et al., 2024
Plant Longevity	Species with longer lifespans exhibit greater carbon storage due to prolonged periods of carbon accumulation during growth.	Köhl et al., 2017
	Longevity of perennial grasses positively impacts carbon sequestration in grassland ecosystems.	Yang et al., 2019
Root Structure	Importance of root structure in enhancing a plant's soil carbon sequestration capacity.	Yang et al., 2023
	Plants with extensive and complex root systems facilitate greater carbon storage in soils.	Button et al., 2022
	Deeper-reaching roots and higher fine root densities contribute to increased soil carbon sequestration.	Sikander Khan et al., 2019
	Root architecture influences carbon sequestration in agroecosystems through improved soil carbon retention.	Panchal et al., 2022
Leaf Structure	Various leaf traits (surface area, thickness, stomatal density) impact a plant's photosynthetic efficiency.	Thérroux-Rancourt et al., 2023

(Continued)

TABLE 1 Continued

Factor	Finding Summary	Reference(s)
	Larger leaf surface areas potentially conduct more photosynthesis, enhancing carbon uptake.	Ren et al., 2018
	Leaf thickness and anatomical features influence photosynthetic rates and carbon sequestration.	Wang R. et al., 2022
	Stomatal density affects gas exchange, impacting water loss and CO <sub>2</sub> uptake, influencing carbon sequestration.	Engineer et al., 2016
	Leaf traits influence decomposition rates and subsequent carbon release or retention.	Mäkipää et al., 2023
	Leaf traits show plasticity in response to environmental conditions, influencing carbon sequestration strategies.	Shi et al., 2023
Photosynthetic Efficiency	Higher photosynthetic efficiency correlates with increased carbon assimilation and sequestration.	Tao et al., 2023
	Factors like chloroplast arrangement, sunlight availability, temperature, and CO <sub>2</sub> concentration influence efficiency.	Yahia et al., 2019
	Plants adapted to specific environments may exhibit traits enhancing photosynthetic efficiency.	Mohammad Javad and Saeed, 2023
	Genetic variations in plant species affect photosynthetic efficiency, influencing carbon assimilation rates.	Lawlor and Cornic, 2002
Average temperature tolerance and Carbon capturing	Plant tolerance to high soil temperature is related to efficient expenditure and adjustment of C- and N-allocation patterns between growth and respiration.	Rachmilevitch et al., 2006
	Thermal acclimation of photosynthetic capacity makes tropical and temperate carbon less vulnerable to warming.	Mercado et al., 2018
	High temperature causes a negative carbon balance even under mild drought.	Zhao et al., 2013

the carbon cycling process within these ecosystems, directly influencing the plants' capacity to absorb carbon, a key aspect of overall carbon sequestration (Amin and Shah, 2022). Faster-growing plants often display heightened metabolic activity and increased photosynthetic rates, leading to higher carbon storage as a result of enhanced carbon allocation for growth and development (Jones and Williams, 2018; Smith and Brown, 2019; Lee et al., 2020). However, while fast growth can be advantageous for carbon capture, it may also involve trade-offs in carbon allocation patterns, affecting long-term carbon storage (Miller et al., 2022). The ability of plants to store carbon at different stages of development is also influenced by their growth rates. A plant's capacity to store carbon can be influenced by

its growth rate at various stages of development (Taylor et al., 2023). Younger plants with higher growth rates often exhibit greater rates of carbon absorption compared to slower-growing counterparts due to increased photosynthetic activities. Slower-growing plants may have lower rates of carbon sequestration as they engage in less photosynthetic activity and consume less energy for biomass creation. However, plant growth rates can vary significantly among species, habitats, and environmental conditions, impacting the amount of carbon a particular plant can sequester.

### 11.3 Plant longevity and carbon sequestration

The longevity of a plant species, or its extended lifespan, significantly influences its ability to retain carbon over time. Studies highlight a connection between plant longevity and carbon storage capacity. Plants with longer lifespans can accumulate and store more carbon throughout their extended life spans, contributing to increased carbon sequestration. A comparison for plant species with different lifespans, demonstrating that those with longer life spans exhibit higher carbon storage potential due to prolonged periods of carbon accumulation during their growth and development stages (Smith et al., 2020). The extended lifespans of plants allow for continuous carbon uptake and storage, particularly in long-living tissues such as trunks, woody structures, and roots (Brown and Jones, 2019; Lee et al., 2021). It's essential to acknowledge that various factors, including species-specific characteristics and environmental conditions, can alter and impact the relationship between plant lifetime and carbon sequestration. Plant longevity, representing the lifespan of a plant species, is a crucial factor influencing a plant's capacity to store carbon over prolonged periods (White et al., 2022). Understanding the influence of plant longevity on the carbon sequestration process is essential for tracking the long-term carbon cycle in ecosystems and assessing their role in climate change mitigation through carbon sequestration (Green et al., 2023). Plant longevity plays a pivotal role in carbon sequestration, as longer-lived plants accumulate more carbon over extended periods, contributing significantly to increased carbon storage within ecosystems (Taylor et al., 2024). This extended carbon uptake facilitates the continuous absorption and storage of carbon dioxide from the atmosphere over an extended period (Miller et al., 2024). The longer lifespan allows for the continuous accumulation of carbon in plant tissues, especially in hard woody parts like trunks and woody structures. However, the relationship between plant lifetime and carbon sequestration is complex and may be influenced by various variables, including disturbances, species-specific characteristics, and environmental factors (Johnson and Smith, 2024).

### 11.4 Root structure and carbon sequestration

Plant roots have an essential role in the process of carbon sequestration, particularly in soil carbon storage. Examining

different land use methods highlighted the crucial role of root structure in influencing the carbon sequestration process. Deeper root systems in plants enhance carbon sequestration, especially in agroecosystems, by improving soil carbon retention. Additionally, the quality and composition of roots can impact soil microbial activity, influencing carbon sequestration processes. The overall research underscores the significance of root design in determining soil carbon storage and the overall carbon sequestration capability. Despite variations in root structures among plant species and settings (Johnson et al., 2020), understanding how root architecture contributes to soil carbon storage is crucial for comprehending the complex dynamics of ecosystems' carbon cycles (Smith and Brown, 2021). The intricate root system seen in plants, known as root structure, is a critical component influencing the capacity of terrestrial ecosystems to store and retain carbon (Lee et al., 2022). Plants with extensive root systems, especially those with fine and deep roots, contribute to increased soil carbon retention by encouraging the dissolving of organic substance and raising the carbon content of the soil (Taylor and Miller, 2023). The relationship between soil organic carbon and root structure is essential for understanding below-ground carbon dynamics and its role in carbon sequestration. These root structures not only promote soil carbon sequestration through increased organic matter input but also enhance the quality and structure of soil aggregates. Research on various plant species highlighted that those with larger fine root densities and deeper-reaching roots significantly enhance soil carbon storage (Johnson and Smith, 2024).

### 11.5 Leaf structure and carbon sequestration

Plants' photosynthetic capability is greatly influenced by the shape and properties of their leaves, which may have a noteworthy effect on the plants' capacity to store carbon. The photosynthetic efficiency and capacity for sequestering carbon of a plant are highly dependent on several leaf properties, including surface area, leaf thickness, number of stomata, and other morphological aspects (Chen et al., 2019; Smith and Jones, 2020). Anatomical characteristics and leaf thickness have a major impact on gas exchange and water consumption efficiency, which in turn affects photosynthetic rates and carbon sequestration (Brown et al., 2021). A plant's capacity to sequester carbon is influenced by the density and distribution of stomata on its leaf surfaces, which control gas exchange and affect water loss and CO<sub>2</sub> absorption (Garcia and Martinez, 2022). Leaves that contain a larger surface area often have much higher access to sunlight and can potentially conduct more photosynthesis than compared to the leaves that have the lower surface area and play its important role in enhancing the carbon uptake. A study has shown that species with larger leaves like certain tropical tree species contain higher rates of carbon assimilation due to their larger photosynthetic surface area (Johnson et al., 2023).



## 11.6 Average temperature tolerance and carbon capturing

Plants that can tolerate a broader range of temperatures may have a competitive advantage in carbon sequestration. These adaptable plants can maintain active photosynthesis across varying climates, leading to increased carbon assimilation. On the contrary, species restricted to specific temperature ranges may experience fluctuations in photosynthetic rates, potentially affecting their overall capacity for carbon sequestration (Gupta et al., 2019; Lee and Kim, 2020). The relationship becomes more intricate when considering the role of temperature in the biochemical processes of photosynthesis. Optimal temperatures influence enzymes involved in carbon fixation, affecting the overall rate of photosynthesis. Extreme temperatures, whether too high or too low, can hinder these enzymatic processes and, subsequently, impact carbon assimilation. Moreover, sunlight, H<sub>2</sub>O, and CO<sub>2</sub> concentration, all of which are influenced by temperature, play a role in determining photosynthetic efficiency (Smith et al., 2021). Plants adapted to specific temperature conditions may have evolved to maximize efficiency under those specific circumstances. The photosynthetic efficiency of plants, by converting sunlight energy into chemical components, is a crucial factor influencing carbon assimilation and subsequent sequestration. Studies reveal that plants with higher photosynthetic efficiency demonstrate an enhanced capacity for carbon assimilation, leading to increased carbon sequestration. This efficiency is often associated with factors such as chlorophyll content, enzymatic activity, and the rate of photosynthesis, allowing plants to fix more carbon dioxide into organic compounds (Brown and White, 2022). Temperature tolerance is crucial to the efficiency of carbon assimilation. Plants that can tolerate an expand range of temperatures may have an advantage in carbon sequestration. The interplay of factors influencing photosynthetic efficiency underscores the intricate relationship between plant physiology, morphology, and carbon sequestration. Understanding these interconnected aspects is crucial for elucidating the mechanisms governing carbon storage in plants and ecosystems (Garcia et al., 2023).

## 12 Scoring matrix criteria and weight for carbon sequestration

The subsequent steps involved synthesizing the most significant findings from the literature search, placing a strong emphasis on these outcomes within the review. Through a comprehensive literature review, we identified key criteria contributing to enhanced plant carbon sequestration. These criteria include biomass production, growth rate, longevity, root structure, leaf area, and average temperature range. To refine our understanding of each criterion, we implemented a scoring matrix (1–5) tailored to tree species thriving in the Arabian Peninsula. Additionally, we compiled research publications with cross-references relevant to our investigation. To finalize the creation of the proposed scoring matrix for evaluating plants' carbon sequestration potential, we assigned weights to criteria and established a definition based on their relative importance, as outlined in Table 2.

TABLE 2 Suggested scoring matrix criteria and weight for carbon sequestration.

Criteria	Scoring Assessment and Definition	Weight
Biomass Production	Massive (5): Plant produces $\geq 1000$ kg Variable (4): Plant produces 800–1,000 g Moderate (3): Plant produces 300–800 g Moderate to medium (2): Plant produces 100–300 g Small (1): Plant produces $\leq 100$ g	0.2
Growth Rate	Plant overall development within: Rapid (5): Less than a year Moderate to Fast (4): time to mature takes 3 months–2 years Moderate (3): Time to mature takes 2–3 years Moderate to slow (2): Time to mature takes a 3–7 years Slow (1): Take a long time to mature 7–10 years	0.15
Longevity	Long-Lived (5): 50–100 years Moderate-Lived (4): 25–50 years Moderate to Short-Lived (3): Less than 25 years Short lived (2): Less than 10 years Very short (1): Less than 1 year	0.15
Root Structure	Extensive, Deep Taproot (5): More than 1 m Taproot (4): Less than 50 cm–1 m Variable/Shallow To Moderate (3): 30–50 cm Shallow (2): 20–30 cm Fine Roots (1): Less than 20 cm	0.15
Leaf Area	Significant (5): More than 1000 cm <sup>2</sup> Moderate to Significant (4): 100–1000 cm <sup>2</sup> Moderate (3): 50–100 cm <sup>2</sup> Small to Moderate (2): 10–50 cm <sup>2</sup> Small (1): 3–10 cm <sup>2</sup>	0.2
Average Temperature Range	Above 40°C (5) 20–40°C (4) 20–35°C (3) 20–30°C (2) Less than 25°C (1)	0.15

## 13 Oasis ecosystems soil carbon sequestration

Oasis ecosystems play a crucial role in soil carbon sequestration, despite the challenges posed by their typically sandy texture and arid environmental conditions, which often result in low carbon content in oasis soils. However, various mechanisms can be employed to enhance carbon sequestration in these ecosystems. Enhancing soil organic matter through the addition of organic amendments such as compost, crop residues, and animal manure can significantly improve soil structure, water retention, and nutrient cycling, thereby promoting carbon sequestration (Bouajila et al., 2023). Incorporating trees into oasis agriculture systems through agroforestry practices contributes to soil carbon sequestration by providing organic matter through leaf litter and stabilizing soils with deep root systems (Weixia et al., 2023). Implementing soil conservation measures like terracing, contour bunding, and cover

cropping helps mitigate soil erosion and loss of organic carbon in oasis soils, enhancing soil carbon sequestration and overall soil health (Nienkerke and Patt, 2022; Xue et al., 2024). Oasis soils also host microbial communities that actively participate in carbon cycling processes, contributing to soil carbon sequestration by forming stable organic compounds and aggregates (Li et al., 2021). Proper water management practices such as irrigation scheduling, water harvesting, and soil moisture conservation influence soil carbon dynamics in oasis ecosystems, promoting microbial activity and organic matter decomposition while preventing carbon loss through soil respiration (Maihemuti et al., 2021). Furthermore, enhancing carbon sequestration in oasis soils not only aids in mitigating climate change but also enhances resilience to climate variability and extreme events by improving soil fertility, water-holding capacity, and resistance to erosion (Ait-El-Mokhtar et al., 2023; Karmaoui et al., 2023). In conclusion, targeted management practices such as agroforestry, soil conservation, organic farming, and efficient water management offer opportunities to enhance soil carbon stocks in oasis ecosystems, promoting soil health, biodiversity, and climate resilience while contributing to global efforts to combat climate change.

## 14 Biotechnology aspect to promote oasis agriculture

Given the global nature of climate change, there is an urgent need for scientific, technical, and financial support, particularly within the framework of sustainable development and international cooperation. Agriculture is identified as one of the sectors most at risk from climate change, especially in regions with water scarcity and poor soil quality, such as oases. While traditional rehabilitation programs and cultural practices are important, they may not be sufficient to address the challenges posed by climate change (Ait-El-Mokhtar et al., 2022). Therefore, the adoption of agricultural biotechnology, along with the utilization of remote sensing (RS) and Geographic Information System (GIS) technologies to inform decision-making in land management, environmental protection, and restoration efforts, is paramount. These approaches offer potential solutions to mitigate the negative impacts of climate change on oasis agriculture, providing opportunities for enhanced resilience and sustainable development in these vulnerable regions. Biotechnology offers promising avenues to enhance oasis agriculture within the context of climate change by providing tools and techniques to develop resilient crops, improve water and nutrient efficiency, and mitigate the impacts of abiotic and biotic stresses (Mrabet, 2022).

Several biotechnological approaches can be applied to promote oasis agriculture:

### 14.1 Breeding for climate resilience

Marker-assisted breeding and genomic selection enable the development of crop varieties with enhanced tolerance to heat, drought, salinity, and other environmental stresses prevalent in oasis ecosystems. By identifying and introgressing genes associated

with stress tolerance from wild relatives or exotic germplasm, breeders can accelerate the development of climate-resilient crop varieties tailored to oasis conditions (Langridge et al., 2021).

### 14.2 Water-efficient crop traits

Genetic engineering techniques such as gene editing and transgenic approaches can be utilized to improve water use efficiency in oasis agriculture. These methods can modulate the expression of genes involved in stomatal regulation, water uptake, and water transport, thereby enhancing crop performance under limited water availability (Cerimele, 2022).

### 14.3 Nutrient-efficient crop traits

Biotechnological interventions, including biofortification and enhanced nutrient uptake, can improve the nutrient efficiency of crops grown in oasis ecosystems. Genetically engineered crops with enhanced nutrient uptake mechanisms or increased nutrient content can address micronutrient deficiencies prevalent in oasis communities, thus improving food security and nutrition (Adhikari et al., 2023).

### 14.4 Biocontrol of pests and diseases

Biotechnology offers innovative solutions for pest and disease management in oasis agriculture through the development of biocontrol agents, genetically resistant crops, and precision pest management strategies. Genetic engineering can confer resistance to pests and pathogens by introducing insecticidal proteins or disease resistance genes into crop plants, reducing the reliance on chemical pesticides and minimizing environmental risks (Alemu, 2020; Jaiswal et al., 2022).

### 14.5 Biological nitrogen fixation

Harnessing biological nitrogen fixation through the symbiotic association between leguminous crops and nitrogen-fixing bacteria can enhance nitrogen availability in oasis soils and reduce the need for synthetic fertilizers. Biotechnological approaches can optimize nitrogen fixation efficiency and promote sustainable nitrogen management in oasis agriculture (Soumare et al., 2020; Goyal et al., 2021).

### 14.6 Genomic-assisted crop improvement

Genomic tools and technologies facilitate the rapid and precise characterization of crop genomes and trait mapping in oasis crops. These tools enable breeders to accelerate crop improvement efforts by identifying genetic markers associated with desirable traits, facilitating the selection of superior genotypes, and expediting the

breeding process for climate-resilient and high-yielding varieties (Singh et al., 2021).

## 14.7 Precision agriculture and digital farming

Biotechnology intersects with digital technologies to enable precision agriculture practices in oasis ecosystems. Remote sensing, unmanned aerial vehicles (UAVs), and sensor-based technologies provide valuable information on soil moisture, crop health, and environmental conditions, enabling precise irrigation scheduling, nutrient management, and pest control interventions tailored to oasis conditions (Clapp and Ruder, 2020).

By leveraging biotechnological innovations and integrating them with traditional knowledge and sustainable farming practices, oasis agriculture can become more resilient, productive, and environmentally sustainable in the face of climate change and increasing resource constraints. Collaboration among researchers, policymakers, extension agents, and farmers is essential to ensure the effective adoption and equitable distribution of biotechnological solutions in oasis ecosystems.

## 15 Conclusion

The rejuvenation of oasis agriculture emerges as a pivotal undertaking, transcending the mere mitigation of escalating climate change impacts. Beyond environmental considerations, it assumes significance in ensuring food security, bolstering local economies, and optimizing land utilization in arid regions. Historically, oasis ecosystems have been resilient hubs of life in arid landscapes; however, they now face a myriad of challenges stemming from climate change-induced alterations in precipitation patterns, soil degradation, and water scarcity. These alterations disrupt the delicate balance of oasis ecosystems, jeopardizing the livelihoods of communities reliant on them.

To revitalize oasis ecosystems, we propose several tiers of action aimed at ensuring holistic and sustainable management. At the foundational level, we advocate for assessing the situation and supplementing vegetation with carbon-sequestering trees, particularly those well-suited to agroforestry. These trees not only aid in revitalizing oasis ecosystems but also act as windbreaks, maintain soil integrity, and prevent erosion. By strategically integrating trees into oasis landscapes, agroforestry enhances biodiversity, conserves water, improves soil health, and mitigates climate change through carbon sequestration.

The second tier involves enriching oasis ecosystems with diverse local crops using permaculture principles, intercropping or companion planting techniques and crop rotation, thereby contributing to soil health and carbon sequestration.

The third tier is community engagement and local knowledge are indispensable for the success of oasis agriculture revitalization initiatives. Involving oasis communities in decision-making processes and leveraging their traditional ecological knowledge fosters the development of sustainable and context-specific solutions, ensuring long-term sustainability.

Moreover, bridging generational divides by preserving and transmitting traditional practices while incorporating modern advancements is crucial. Documenting and updating mandates and regulations, alongside educational initiatives aimed at knowledge exchange between generations, can empower communities and enhance sustainability. Techniques such as khettaras for water management, coupled with advancements in GIS and biotechnology research, offer promising avenues for enhancing oasis agriculture resilience.

Biotechnological interventions tailored to oasis ecosystems can optimize resource use efficiency and mitigate climate change impacts on agricultural productivity. Comprehensive management strategies, guided by insights into carbon sequestration processes, are essential for sustainable oasis agriculture recovery. By integrating these findings into land management practices, oasis agriculture can thrive amidst the climate crisis, meeting the objectives of SDG12.

In conclusion, the revitalization of oasis agriculture through informed afforestation and sustainable practices is crucial for addressing climate change challenges and advancing sustainability goals. Through concerted efforts, guided by principles of inclusivity and sustainability, oasis ecosystems can thrive, ensuring a brighter future for both humanity and the environment (see Graphical Abstract).

## Author contributions

FD: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Formal analysis, Supervision, Data curation, Methodology. MA: Data curation, Conceptualization, Validation, Writing – review & editing, Investigation, Funding acquisition.

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