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Review

Thar Desert Bioresources: Significance, Conservation and Sustainable Management in Anthropocene

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ABSTRACT
'Anthropocene', the era of earth's history during which human (*Homo sapiens*) have become a dominant geological force. The anthropogenic activities have irreversibly impacted the globe, the atmosphere, and therefore the climate system as a whole. The global warmings associated with climate changes and other constraints such as small landholdings, lower land productivity, water stress, especially in drylands increased vulnerabilities to the local inhabitants. Indian Thar Desert, a unique stressed ecosystem, harbours diverse life-forms (plants, animals and microbes) having acquired mechanisms of survival under fragile conditions (biotic and abiotic stress, especially recurring droughts). These extremes in the climatic, edaphic and topographic regimes provided the exceptional natural environmental conditions for origin, growth, adaptation and evolution of variety of life-forms. Desert specific species harbours traits/genes such as heat, drought, salt tolerance, etc. that may be important to answer the challenges being caused by anthropogenic disturbances. The natural resource management through agroecology and agroforestry systems practiced by the native people is the best option as an insurance in case of crop failure due to environmental circumstances. In this paper, we review the present scenario of biological diversity of desert, human induced/anthropogenic threats/constraints to arid/semi-arid ecosystem and geo-ecological parameters. The possible solutions to some of these problem through intervention of innovative technologies are also discussed.

Key words: Anthropocene, Biotechnological tools, Conservation, Fragile Ecosystem, Renewable Energy Sources, Thar Desert

INTRODUCTION

The climate system has a central role and sets the boundary for our lives on the earth (Folke et al. 2021). The human actions significantly restructured and altered relations between climate and biosphere. Also, the capacity of forests, oceans and other ecosystems to sequestrate CO_2 emissions and to store huge quantities of greenhouse gases in peat lands and soils have also been affected by manmade activities (Steffen et al. 2018). Ciais et al. (2014) stated that the total amount of carbon stored in terrestrial ecosystem (of which, about 70% in soil) is sixty-fold higher than the global greenhouse gases emission by human beings. According to Olsson et al. (2017) increased CO_2 concentration and climate change are the most noticeable pointers of the human influence. It has estimated that increased emissions of greenhouse gases caused serious climatic shocks as 1.2^{o}C warming has been observed in comparison to pre-industrial levels (WMO 2020). The UN Intergovernmental Panel on Climate Change (IPCC) published a "Special Report on 1.5 Degrees" (October 2018) cautioning that 1.5°C decrease in global temperature would necessitate immediate, extensive and unparalleled reforms throughout the world (IPCC 2018). Climatic stability of the biosphere is a crucial ecosystem service or earth system service which cannot and should not be taken for granted. Climate changes coupled with other constraints such as small landholdings, low land productivity, water stress, especially in desertic regions contributes towards increasing vulnerability to the local communities (Singh and Chudasama 2021). According to Shekhawat et al. (2014a), about 45 to 47% of the earth's land surface is covered by arid regions (drylands), which is the largest biome of the world and about 38% of global populations reside here. Ecosystems of these arid and semi-arid regions are highly fragile and sensitive to anthropogenic activities; however, harbour considerable biodiversity rendering ecosystem services (Shekhawat et al. 2014b, IPCC 2018, Ramarao et al. 2019).

Besides having the extreme climatic conditions and hostile environment, Thar desert is one of the thickly populated hot deserts of the world and hosts large number of human and livestock populations. These populations laid various type of pressures on the biodiversity of desert and may bring unsustainability in near future if immediate conservation actions are not taken (Singh 2004). This review paper discusses a few major aspects related to Indian Thar desert such as bioresources of arid ecosystem, anthropogenic threats/socioeconomic pressures, measures for ecosystem restoration, geo-ecological environmental conditions, etc. There is immediate need to expand research in every possible direction to answers issues related to conservation, sustainable utilization and management of bioresources of fragile ecosystem. The potential, scope, current status and future perspective of renewable energy resources have been discussed. Also, efforts for development of biotechnological tools/techniques for characterization, conservation and rehabilitation of bioresources in Thar desert in past few decades have been presented.

METHODOLOGY

A general methodology for present study includes periodic field visits to the arid and semi-arid regions (Sri Ganganagar, Hanumangarh, Jaisalmer, Bikaner, Barmer, Churu, Nagaur and Jodhpur) of the great Indian Thar desert. Frequent interactions were made with the researchers from various scientific institutions located in these areas such as Central Arid Zone Research Institute (CAZRI), Jodhpur; Arid Forest Research Institute (AFRI), Jodhpur; Arid Zone Regional Centre, Botanical Survey of India (BSI), Jodhpur; ICAR-National Bureau of Plant Genetic Resources (NBPGR), Jodhpur; ICAR-Agricultural Technology Application Research Institute (ATARI), Jodhpur; Agriculture University, Jodhpur; Indian Institute of Technology (IIT), Jodhpur; Jai Narain Vyas University, Jodhpur; Krishi Vigyan Kendra (KVK), Jaisalmer; Swami Keshwanand Rajasthan Agricultural University, Bikaner and Maharaja Ganga Singh University, Bikaner, etc. Random interviews were conducted with the local inhabitants (at least 10 persons from each district under study) to know the traditional knowledge/cultural practices related to sustainable utilization, management and conservation of biodiversity in the study area. Photography was also done in support to record the relevant activities/information. Literature survey was conducted using Google Scholar™, Web of Science™, ResearchGate search engines during 2018 to 2021. All the botanical names were confirmed/verified (URL-1).

‘Anthropocene’ a new geological series/epoch?

“We are in the Anthropocene” as declared by Nobel Prize-winning Dutch meteorologist Paul Crutzen in February 2000 (Crutzen 2002). The growing impact of human activities on the globe and the atmosphere appeared in newsletter of the International Geosphere-Biosphere Programme (IGBP;Crutzen and Stoermer 2013). The dominating human nature and unsustainable exploitation of resources from the mother earth resulted in global warming and climate change (Malhi 2008). Besides, the Anthropocene also included loss of biodiversity, modifications in biogeochemical cycles, extensive resource exploitation and various types of waste creation. The current geological epoch ‘the Holocene’ is no longer applies to only Anthropocene where human interference has irrevocably influenced the global atmosphere (Crutzen and Stoermer 2013, Carey 2016). According to Ros (2021), the ‘Anthropocene’ is still an informal term and the process of formalization is still due, although it is commonly used in majority of scientific and non-scientific literatures. Another alternative to the Anthropocene ‘the plantationocene’ in which plantation, agriculture, variation in plantation (during time and space) and their socio-ecological penalties have appealed our attention (Haraway et al. 2015, Davis et al. 2019). For this, the Anthropocene Working Group has been attempting to establish ‘Anthropocene’ as a new epoch/series following the Holocene as per the International Chronostratigraphic Chart since 2009. This could only be possible if persons from academics, politics, humanity, policy makers and other stakeholders come together to define an age of the earth.

Geo-ecological environment of Indian Thar Desert

The Indian Thar desert covers 2.34 million km^2 and recognized as one of the most hostile, even densely populated hot arid regions of the world (Chauhan 2003). It occupies the western Rajasthan (61.9%), Gujarat (19.6%), south-western Punjab and Haryana (8.6%) and other states (Moharana 2017). The sandy arid land of Rajasthan is known as Marusthalli (the land of death) which is characterized by shifting and stabilized sand-dunes of several forms, sizes and alignment (Fig. 1a). The aeolian and ephemeral landforms (shifting sand-dunes) are the characteristics features of the Thar Desert landscape. Almost 48% area of western Rajasthan is covered by sand-dunes (the major aeolian landform). Other landforms include several types of hills, valleys, dykes, ridges, pediments, pediplains of variable origin and morphology (Moharana et al. 2016). A few inland rann (saline depressions/playas) are also recorded here. Owing to prolonged/stretched and multifaceted geological history ranging from the Palaeozoic and the Mesozoic to the Coenozoic era, the Thar Desert is recognized for the various localities of global significance encompassing fossils of plants and animals (Pandey et al. 2010, Chlachula 2021).

Rajasthan has three National Fossil Parks, out of which Akal Fossil Wood Park is spread across 21 hectares area and named after its location in Akal village (26°492 303 N 71°022 243 E), 18 km from Jaisalmer (Ranawat 2020). Also, the Desert National Park (DNP), gazetted in 1980, is a UNESCO World Heritage Site ranges-over an area of 3162 km^2 of Jaisalmer and Barmer districts of Rajasthan (Fig. 1b). The Thar Desert has harsh climatic conditions such as high temperature (up to 50^{o}C in summers), low relative humidity, high evapotranspiration, low precipitation and high wind velocity (Shekhawat et al. 2012a). This desert receives an average annual rainfall (342 mm) with a minimum of 130 mm annual rainfall in the western most arid regions (Singhvi and Krishnan 2014). The atmospheric water demand (evapotranspiration) is about 1400 to 2000 mm which adds fragility to the environmental conditions of the Thar Desert (Moharana et al. 2016). Furthermore, in

Figure 1. (a) Sand-dunes at Sam, Jaisalmer; (b) The Desert National Park (DNP) ranges in Jaisalmer and Barmer districts of Rajasthan

comparison to four months in most of the India, this desert receives rainfall during Monsoon (south-west) season (July to September) for 2.5 to 3 months only. The arid zone of Rajasthan has 1486 X 106 m^3 (only 7.2 mm in depth) surface water resources in total, except IGNP (Indira Gandhi Nahar Pariyojna) (Goyal and Gaur 2016). These extremes in the climatic, edaphic and topographic regimes provide exceptional natural environmental conditions for origin, growth, adaptation and evolution of variety of plants, animals and microbes.

Bioresources of Indian arid ecosystem

The Indian Thar Desert is a unique stressed ecosystem harbouring diverse life-forms with acquired mechanisms of survival under fragile conditions. For assessment of biodiversity and ecosystem services of a particular region, the land cover is the most critical component. Indian Desert inhabits a variety of herbs, under-shrubs, shrubs, trees, vines, lianas, grasses, hedges, etc. The inhabitants grow/cultivate about 275 species as sources of grains, pulses, oilseeds, vegetables, fruits, spices, herbal medicines, fodder, ornamental and avenue plants (Shekhawat et al. 2012a). According to Shetty and Singh (1993), about 17 plant species are endemic to this region and nearly 65 species are probable wild relatives of fruit crops or crop plants, indicating this region as a centre of speciation.

The livelihood of native people majorly depends up on rain-fed agriculture and ecosystem services. The major agricultural, horticultural and forestry practices in this region are non-intensive and people favours organic farming which are beneficial for environment/eco-friendly. These practices also mitigate uses of chemical pesticides, fertilizers and other pollutants. Rajasthan is recognized for the production of several climate resilient (C_4) cereals/grains, such as pearl-millet (*Cenchrus americanus* [L.] Morrone syn. *Pennisetum glaucum* [L.] R. Br., Bajra/Bajri), great millet (*Sorghum bicolor* (L.) Moench, Jowar/Jowari), etc. According to Choudhary et al. (2021), there are numerous locally adapted pearl-millet landraces germplasm available that can be exploited in crop improvement programmes in the changing climate. In spite of harsh climatic conditions, Rajasthan have been remained at the top in the production of pulses in the country. The major pulse crops are the green-gram (*Vigna radiata* (L.) R. Wilczek, mung bean), the Moth-bean (*Vigna aconitifolia* (Jacq.) Marechal), the Chickpea (*Cicer arietinum* L., gram), the cowpea (*Vigna unguiculata* (L.) Walp., black-eye pea), etc. The Guar (*Cyamopsis tetragonoloba* [L.] Taub.), another legume, is a highly prioritized industrial crop and Rajasthan is the world's number one producer of Guar (Fig. 2a; Sharma et al. 2014). Rajasthan has significant contribution in production of oilseed crops such as *Sesamum indicum* L. (til; Fig. 2b) and *Arachis hypogaea* L. (groundnut). This state is the largest contributor of rapeseed-mustard in the country and account for 44.9% production in 40.7% area (Chand et al. 2021).

A number of vegetable and fruit species occurs in this region namely, Sangari, Kumbhat, Ker, Gunda, Mirchi, Phog, Piloo, Ber and a variety of cucurbits. Local people use processed/preserved Sangari (immature pods of *Prosopis cineraria* (L.), Khejari) along-with Kumbat (seeds of *Acacia senegal* (L.)

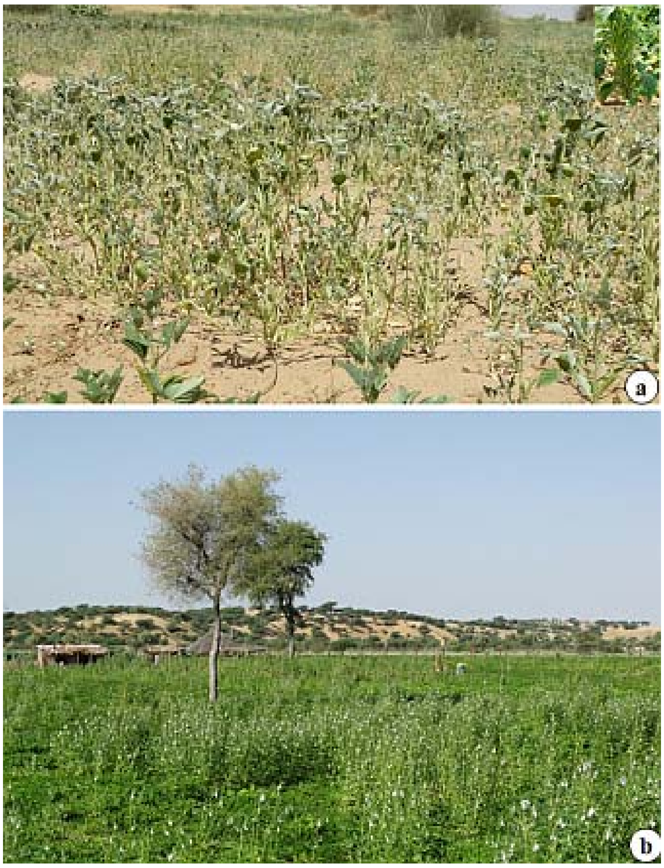

Figure 2. (a) *Cyamopsis tetragonoloba* (guar), a drought-tolerant legume; (b) *Sesamum indicum* (til), an important oilseed crop. *Prosopis cineraria* growing in til field, a beautiful example of agroforestry system.

Willd.; Fig. 3a), (tree), inset (seeds) Ker (unripen fruits of *Capparis decidua* (Forssk.) Edgew.), Gunda (unripen fruits of *Cordia myxa* L.) and Mirchi (ripened fruits of *Capsicum annuum* L.) is the five ingredient of the famous Rajasthani cuisine **'Panchkuta'** (in Hindi). The flower buds (Phugusi/Lasson) of *Calligonum polygonoides* Linn. sp. Hook (Fig. 4d) are mixed with buttermilk to make heat relieving Raita in summers. The ripened fruits of Ber (*Ziziphus nummularia* [Burm. f.] Wight & Arn.) and *Z. mauritiana* Lam. (Fig. 3b) are richer in carbohydrates, proteins, vitamin – C, calcium and phosphorus in comparison to the apple (Rathore 2009). The ripened fruits of *Salvadora oleoides* Decne. (the Meetha-Jal (Fig. 4a); fruits: Piloo/desert grapes), loaded with glucose, fructose and sucrose are preserved by native people for offseason consumption (Rathore 2009, Arora et al. 2014).

In spices, Nagauri methi (*Trigonella* species),

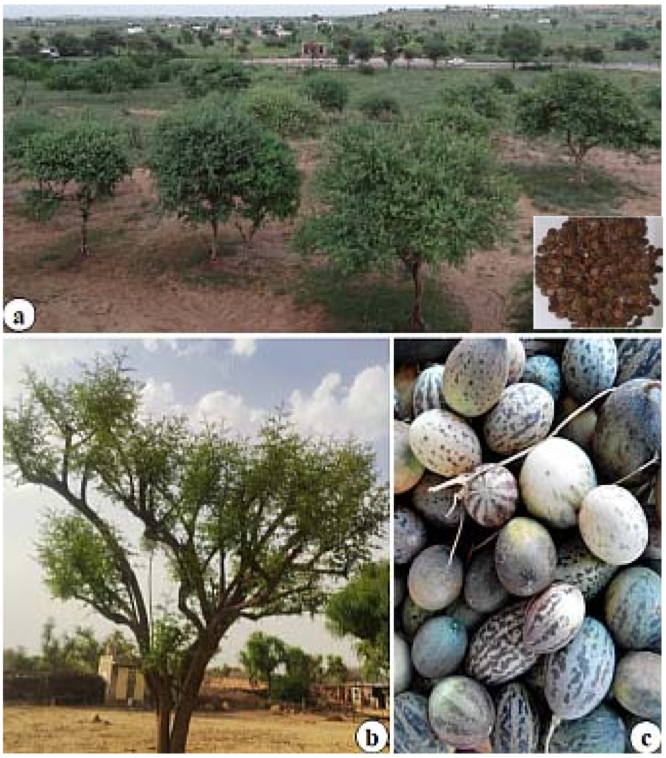

Figure 3. (a) *Acacia senegal* (the Kumbat) naturally growing near Dechu region; (b) *Ziziphus mauritiana* (bordi), a horticulturally important plant; (c) Wild and indigenous *Cucumis* species, a diverse genus found in Thar desert

prevalently cultivated in the Nagaur district of Rajasthan is world known for its characteristic's fragrance/aroma. It is an important commodity being exported worldwide and requires Geographical Indication (GI) tag immediately. The world famous Mathania mirch/mirchi (*Capsicum annuum* L.), a valued spice for export and recognized for its sourness, is another candidate requiring GI tag, although facing danger of becoming obsolete (Vyas and Kumar 2002). The Jeera/Cumin (*Cuminum cyminum* L.) is another important cash crop of the World. India contributes more than 75% cumin production; of which Rajasthan and Gujarat give more than 90% (Rowniyar and Yadav 2021).

Rajasthan offers a great genetic diversity of wild and indigenous cucurbits which naturally grows on field-walls during monsoon and provide food, livelihood and nutritional security to the indigenous people (Choudhary and Shekhawat 2018) (Fig. 3c). Some of them are Kachari (*Cucumis melo* var. *agrestis*), Snap-melon (*Cucumis melo* var. *momordica*), Spine-gourd (*Momordi ca dioica* Roxb. ex Wild.), Desi-karela (*M. balsamina* L.), Tinda/ Tindsi (*Praecitrullus fistulosus* (Stocks) Pangalo), Matira/Water-melon (*Citrullus lanatus* var. citroides (L. H. Bailey) Mansf., Ridged gourd (*Luffa acutangula* (L.) Roxb.), etc. In grasses, *Lasiurus scindicus* Henrard (sewan; Fig. 4b) and *Cenchrus ciliaris* L. (dhaman) are important perennial hardy grasses growing on sand-dunes have great soil binding potential and therefore, suitable for soil conservation. These grasses are source of nutritional green-fodder for cattle and Marwari horses, even under low rainfall circumstances (Soni et al. 2013).

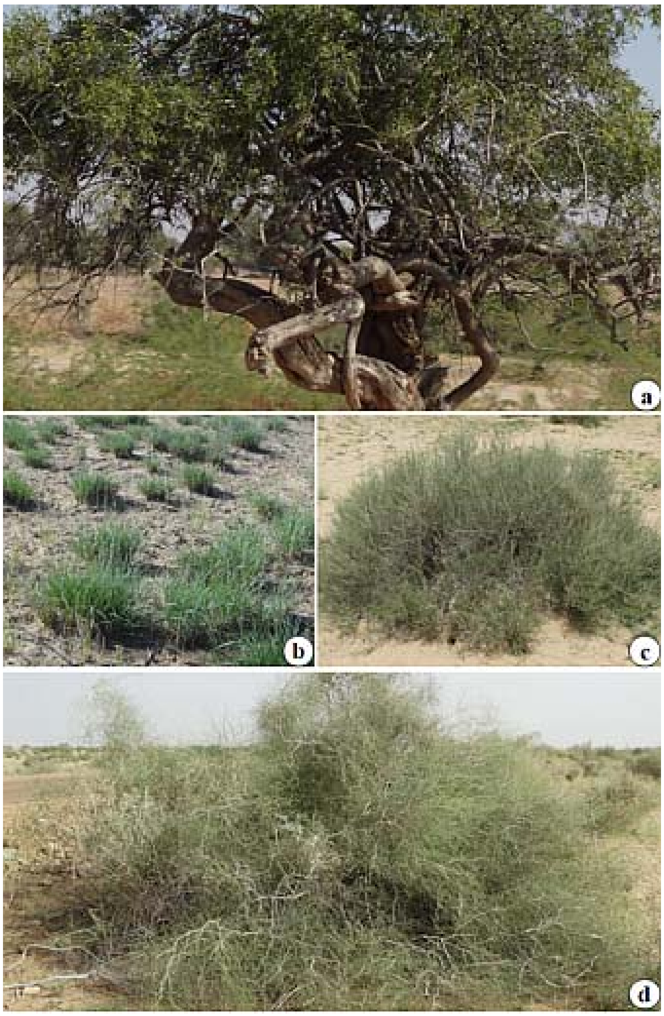

Figure 4. (a) *Salvadora oleoides* (meetha-jal); (b) *Lasiurus scindicus* (sewan), an important perennial hardy soil binding grass; (c) *Haloxylon salicornicum* (barilla or sajji-khar), a halophytic species; (d) *Calligonum polygonoides* (phog), a sand-dunes stabilizing plant

Halophytes species from Indian Thar desert have been identified for bioethanol or biofuel production as well as their supplementary role in sustainable development. According to Sharma et al. (2017), the consistently increasing need of biofuel production makes these halophytes as promising “green gold” in the near future. Some important halophytic plant species from Indian Desert are *Salsola baryosma* (Schult.) Dandy (Chenopodiaceae), *Suaeda fruticosa* (L.) Forssk. (Chenopodiaceae), *Salvadora persica* L. (Salvadoraceae), *Sesuvium sesuvioides* (Fenzl) Verdc. (Aizoaceae), *Trianthema triquetra* Willd. (Aizoaceae), *Sporobolus helvolus* (Trin.) T. Durand & Schinz (Poaceae), *Zygophyllum simplex* L. (Zygophyllaceae). Also, a few halophytic species are economically important such as *Haloxylon salicornicum* (Moq.) Bunge ex Boiss. (Fig. 4c) (Amaranthaceae) is a source of crude sodium carbonate (barilla or Sajji-Khar) used as a key ingredient in the world famous Biknaeri bhujiya (a product having GI tag; URL-2).

A number of perennial tree species are source of biomass production to support life and provide ecosystem services in the most populated desert of the world. The major tree species are *Prosopis cineraria* (L.) Druce, *Tecomella undulata* (Sm.) Seem., *Acacia senegal* (L.) Willd., *Acacia nilotica* (L.) Delile, *Salvadora persica* L., *Salvadora oleoides* Decne., *Zizyphus* species. Among these, *P. cineraria* is the keystone species of this region on which other species depends, survive and perform important eco-physiological functions more than its relative biomass production (Gehlot and Kumari 2018). In shrubs, *Capparis decidua* (Forssk.) Edgew., *Gymnosporia emarginata* (Willd.) Thwaites (Syn. *Maytenus emarginata* (Willd.) Ding Hou, *Calligonum polygonoides* L., *Leptadenia pyrotechnica* (Forssk.) Decne., *Calotropis procera* (Aiton) Dryand., *Ephedra foliata* Boiss. ex C. A. Mey., etc. are some important species in this region. The Thar Desert is endowed with numerous herbal plants having medicinal, therapeutics and nutraceutical values. National Medicinal Plants Board (NMPB), Ministry of AYUSH, Government of India has prioritized 55 plant species, of which many of them propagates very well in the Indian Thar Desert such as *Asparagus racemosus* Willd. (satavari), *Senna alexandrina* Mill. (senna), *Chlorophytum acutum* (C. H. Wright) Nordal (safed musli), *Commiphora wightii* (Arn.) Bhandari (guggal), *Glycyrrhiza glabra* L. (mulathi), *Plantago ovata* Forssk. (isabgol), *Tinospora sinensis* (Lour.) Merr. (Syn: *Tinospora cordifolia* (Willd.) Miers) (giloya), *Withania somnifera* (L.) Dunal (ashwagandha), *Aloe vera* (L.) Burm. f. (ghritkumari), *Boerhavia diffusa* L. (punarnava), *Clerodendrum phlomidis* L. f. (Arni), etc (URL-3). The plant, animals and microbes thriving in extreme arid/xeric conditions tolerates numerous abiotic stresses for their survival. These species have evolved and developed mechanism to combat the harsh environmental hostilities. The desert bioresources' products (nutraceuticals, bioactive compounds) may be the potential candidates for bioprospecting and supposed to be the assets of the country. Desert specific species harbours traits/characters such as heat, drought, salt resistance/tolerance that may be important for breeders, geneticists, environmentalists, biologists, etc. to answer the challenges of anthropogenic disturbances, including global warming/climate change.

Anthropogenic activities and threats to the desert bioresources

According to the Organisation for Economic Co-operation and Development (OECD 2012), biodiversity loss occurs through the five key factors: (i) habitat destruction (ii) overexploitation and unsustainable utilization (iii) environmental pollution (Fig. 5a) (iv) introduction of alien/exotic/invasive species and (v) climate change. The wide-spread habitat loss/fragmentation (Fig. 5b) in the Thar Desert triggered by ever-increasing human population, developmental activities on established sand-dunes, expansion of agricultural land, extensive utilization of power-operated machines, mining activities (sandstone, limestone, marble, granite, gypsum, lignite, etc; Fig. 5c), have formed terrible environmental situations that are supposed to be alarming/serious for ecology and living creatures. The other major threats include soil erosion, contamination of water bodies (especially by tie and dye industries), various types of biotic and abiotic stresses, introduction of fast-growing alien/exotic/ invasive species under afforestation programmes without their proper environmental impact

Figure 5. (a) Environmental pollution by factories/ industries; (b) Habitat loss/fragmentation; (c) Uncontrolled mining activities; (d) Introduction of alien/exotic/invasive species under afforestation programmes without environmental impact assessment

assessment (e.g. *Acacia tortilis* [Forssk.] Hayne, *Prosopis juliflora* [Sw.] DC., Fig. 5d), etc (Singh 2004, Mukherjee et al. 2017). The superior looking alien species eliminated or put the endemic, rare, endangered and threatened (RET) plant species under threat which have slow growth/propagation and poor reproductive abilities (e.g. seed setting and seedling establishment). These disturbances have not only changed the natural landscape of the desert but also affected the local drainage system in some regions (Moharana et al. 2016). The Indian Desert has uncertain rainfalls and experienced the flood attack in September 2006 (the Kwas Flood, named after a village in Barmer district) and took lives of several living beings.

Eco-restoration in Thar desert

According to Sinha and Sinha (2000), desertification is supposed to be a silent crisis, which deteriorate the land productivity and badly affects people and livestock populations and interrupts ecosystem services. A multidisciplinary approach with united actions from academician, policy makers, native inhabitants and other stakeholders are necessary to combat desertification and rehabilitation of desertic land for restoring its productivity. The recovery of

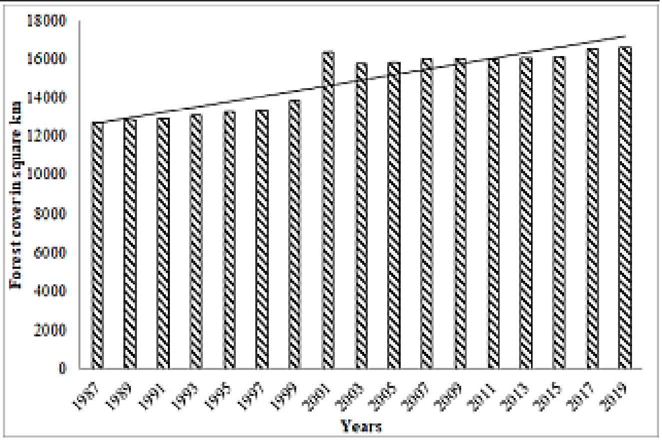

Figure 6. Trends showing increasing forest cover in square km area during 1987-2019 in Rajasthan

degradation against water deficiency, groundwater salinity and nutrient loss is challenging task which requires long term sustainable priorities such as cultivation of innovative crops, diversification of agriculture, avoiding overgrazing, etc. Figure 6 showing the trends of increasing forest cover in square km area during 1987-2019 in Rajasthan (URL-4).

The government of India is contemplating a plant to develop a 1400 km long and 5 km broad green belt right from Gujarat to Delhi-Haryana border; similar to the 'Great Green Wall' of Africa running from Dakar to Djibouti to cop-up climate change and desertification (URL-5). This will not only help in restoring degraded land through afforestation along the Aravalli hills but also act as a barrier for eastward movement of the Thar desert and check dust coming from the western India and Pakistan. Furthermore, wastewater can be used as an alternative source of water in dryland afforestation programmes. Available reports suggest that some tree species such as *Acacia nilotica*, *Azadirachta indica*, *Eucalyptus camaldulensis*, *Prosopis cineraria*, *P. juliflora* are best suited species in growth and biomass production using wastewater (Singh et al. 2021).

For protection and conservation of the rare fauna of the region, the UNESCO has assured to provide financial assistance and technical support. This project may shortly be included in UNESCO's Man and the Biosphere (MAB) Programme. This practice has been continuing for last three decades and now the latest proposal has been prepared in association with the CAZRI, Jodhpur, to announce it as a biosphere reserve for conservation of flora and fauna and protection of the Thar desert's fragile ecosystem (URL-6). The policies related to environmental issues are generally framed for long-term duration and larger benefits of mother nature/mother earth. In majority of cases, the results are found positive (e.g. Indira Gandhi Nahar Pariyojna), however there are always chances of diffused outcomes (e.g. Introduction of *Acacia tortilis* and *Prosopis juliflora* under afforestation programs).

Sustainable utilization of bioresources

The advancing threats caused by anthropogenic activities, habitat loss/fragmentation, land degradation, coupled with the effects of global warming/climate change, continue to put the security and stability of the world's population at risk. There is prerequisite to design, develop and implement alternative measures to address the challenges imposed by Anthropocene to build a more stable, secure, sustainable and resilient future. According to Xu and Tan (2020), natural resources are the ultimate source of energies and human economic activities which determine the way and structure of global economic development. The sustainable pathway for economic development is very likely to be achieved if biodiversity is well managed. The products and services provided by biodiversity and ecosystem help in sustainable development at various levels. To develop stable and secure livelihood and climate resilient services, there is need of agricultural diversification through cultivation of herbal/ medicinal plants, adoption of animal husbandry (especially small ruminants), processing, packaging of value-added products and inclusiveness of market integration approaches (Kumar et al. 2017).

In 2007, the Food and Agriculture Organization (FAO) has assisted the Great Green Wall (GGW) initiative, a game changer for Africa, to alleviate and combat desertification, exterminate poverty, end starvation, boost food and nutritional security and to address climate change issues. This was an example of transformative model for sustainable development of rural communities in Africa (UNCCD Report 2020). Similarly, the objectives of Indira Gandhi Canal, a leading canal projects in India, were to provide drinking water, support livestock and afforestation programmes, drought proofing, employment, rehabilitation, environment improvement and increase agricultural yield in Rajasthan (Shekhawat et al. 2012a).

Regardless of recurrent droughts, this region has an agricultural dominated economy. Therefore, the priorities in sustainable land management in this region should be drought proofing through combination of traditional as well new drought-coping approaches. This may be achieved using climate-ready cultivars, utilization of economically important perennials, soil and water conservation, rainwater harvesting and its resourceful application for high value produces, and involvement of institutional and traditional knowledge. The agroecology and natural resource management practices perfected by local people over a period of time are regarded as Traditional Ecological Knowledge (TEK). For instance, *Prosopis cineraria* (L.), the Khejari, is a highly valued leguminous tree species of Indian desert ecosystem and the most accepted tree of arid agroforestry. Khejarali sacrifice of 363 Vishnoi community people in the year 1730 is one of the best examples of the love, affection and gratitude towards the Mother Nature (Shekhawat et al. 1993).

The people of western Rajasthan have developed a number of agroforestry systems as the best option as insurance against sole crop failure due to recurrent droughts (Fig. 2b). In this approach, farmers allow growing/developing scattered trees and shrubs in their farms or grazing field, especially for their environmental services and produces such as wind protection, soil conservation, bio-fencing (natural boundaries), shelterbelt, food, fodder as well as fuel wood (Subbulakshmi et al. 2018). The Planning Commission of India has identified fifteen agro-eco regions (AEZs) for effective resource management. Of these, the Western Dry Region spread over nine districts of Rajasthan. There is need for participatory agroecosystems that can support farmers in resilient and profitable farming systems (Varghese and Singh 2016). For conservation, utilization and management of Thar desert bioresources, there is need for stakeholders to act on multidisciplinary approaches with united actions from all possible fields (academician, policy makers, native inhabitants and others) by adopting sustainable utilization strategies and development of innovative techniques for their efficient consumption.

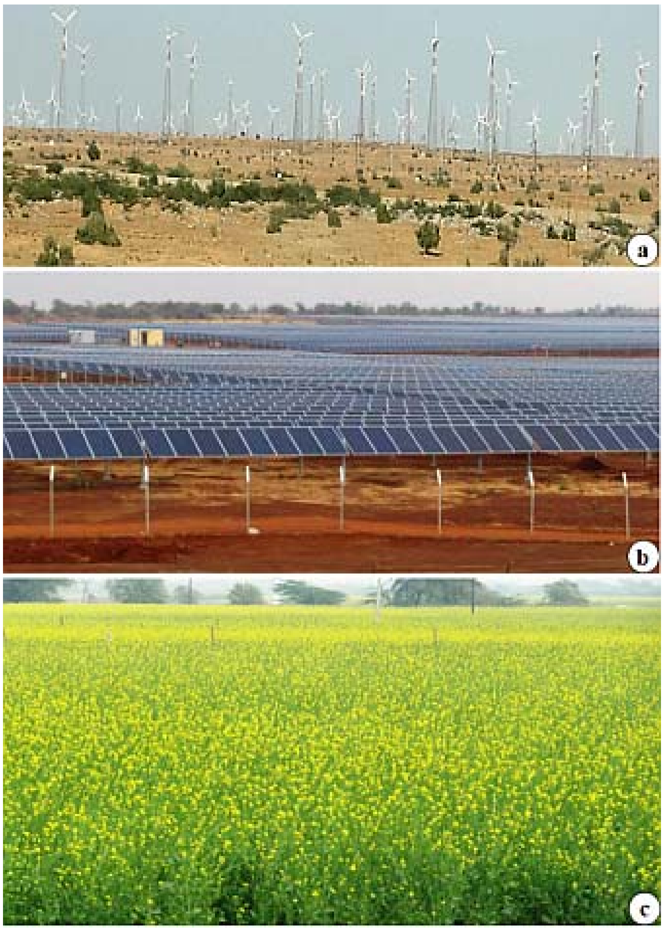

Figure 7. (a) Established wind mills/energy set-up near Jaisalmer; (b) Bhadla Solar Park, the largest solar park in the world as of 2020 (total capacity: 2245 MW); (c) *Brassica* species, a major biomass producing plant

Rajasthan: a hub of renewable energy resources

Owing to the geographical conditions, Rajasthan has a great potential in the renewable/alternative energy sector. Rajasthan holds fifth position in India in electricity production from renewable resources such as solar, wind and biomass energy (Bhukya et al. 2021). High radiation, wind speeds and presence of hectares of barren plains are the key factors that make Rajasthan state as a perfect location for establishment of renewable energy plants (wind energy and solar power projects; Fig. 7a and b). As per the United States Department of Energy, Rajasthan state occupies the second position in receiving the largest amount of solar radiation in the world. Here, the positive aspect is that about 89% days in a year are sunny and receives 6-7 kWh/sq-m/Day solar radiation (Bhukya et al. 2021). The western part of Rajasthan includes four districts namely, Jaisalmer, Barmer, Bikaner and Jodhpur. These districts are the main centres and have a great potential of solar energy production. Owing to maximum solar radiation absorption, Jodhpur is also known as the Sun City of India (Meena et al. 2014). The total installed capacity of ground mounted solar energy is 4996.96 MW excluding 356.80 MW from solar roof top under net metering scheme up to September 2020 (URL-7). Rajasthan stand at the fifth position in wind power having capacity of 4337.64 MW in the year 2019-20 and covers about 20% of wind sector in India (Paliwal and Dave 2021, Bhukya et al. 2021). The Jaisalmer Wind Park (Rajasthan) is one of the biggest operative wind farms and established chiefly by the Suzlon Energy Limited, Pune, India and other companies (Paliwal and Dave 2021) (Fig. 7a). The state nodal agency is Rajasthan Renewable Energy Corporation Limited (RRECL) and projects are developed and run by Suzlon, Enercon (World Wind India) and Inox (Sharma and Sinha 2019). Ministry of New and Renewable Energy sources (MNRE), Government of India as well as Department of Energy, Government of Rajasthan has launched various schemes and developed policies to encourage the industrial and domestic sector to adopt renewable energy sources. Rajasthan has set a target to produce 22000 MW power using solar and wind energy in 2022.

India holds seventh position in the world for bioenergy production (450-500 MPY; Bhukya et al. 2021). The major biomass producing plants of Rajasthan are Mustard husk (*Brassica* species; Fig. 7c), Guar stalks (*Cyamopsis tetragonoloba* (L.) Taub.), Castor stems (*Ricinus communis* L.), Cotton stalks (*Gossypium* species) and Julieflora (*Prosopis juliflora* (Sw.) DC.). Approximately 11,62,679 tons/ year of mustard stalks; 6,96,922 tons/year of Guar stalks; 5,07,715 tons/year surplus of Castor stems followed by many other crop residues can be utilized as feedstock in the electric power generation (Jain 2016). In Rajasthan, the first biomass plant was set up by Kalpataru Power Transmission Limited (KPTL) in Ganganagar district of Rajasthan in 2003 of 7.8 MW capacity. Later on, in 2006 KPTL had set up another plant in Tonk district of 8 MW. Both of these plants are successfully generating powers from their establishment. As of September 2020, the total capacity of biomass energy production in Rajasthan has reached up to 120.45 MW (URL-7).

Biotechnological strategies for conservation and utilization of bioresources

Biodiversity conservation is a multifaceted process that can be achieved through habitat protection (*in situ*) as well as through development of biotechnological techniques (*ex situ*). *In situ* and *ex situ* conservation methods are the two fundamental approaches that requires comprehensive understanding of available bioresources. Biotechnological measures have emerged as a widespread tool for conservation, management and sustainable utilization of biodiversity in the best way (Rajasekharan 2017). Plant biotechnology has made a significant contribution in the past few decades in phytodiversity conservation of the Thar Desert using various techniques such as micropropagation, organogenesis (direct or indirect), somatic embryogenesis, cell suspension culture, encapsulation technology, DNA markers, etc (Shekhawat et al. 2012a). In addition, somatic cell genetics, molecular characterization, biochemical profiling and gene/genetic manipulation/ transformation have also contributed in the improvement of desert specific plant species. Also, the speed and efficiency of crop improvement programmes can be significantly enhanced using application of biotechnological tools as compared to conventional breeding programmes (Shekhawat et al. 2012b). Plant cell, tissue and organ culture is used globally as a non-GMO (genetically modified organism) biotechnology for large scale propagation/ mass-multiplication (Fig. 8a and b) and secondary metabolite production (Lodha et al. 2014, Shekhawat et al. 2014c). Plants provided through tissue culture can reduce excessive pressure on their natural populations and assists in providing accessible raw material for extraction of various bioactive/ therapeutic/nutraceutical compounds/principles from plant species such as *Commiphora wightii* (Yusuf et al. 1999), *Arnebia hispidissima* (Lehm). DC. (Shekhawat and Shekhawat 2011, Ram et al. 2022a), *Lawsonia inermis* Linn. (Ram and Shekhawat 2011, Ram et al. 2022a), *Momordica dioica* (Roxb.) (Shekhawat et al. 2011), *Ceropegia bulbosa* Roxb. (Phulwaria et al. 2013), *Caralluma edulis* (Edgew.) Benth. & Hook. f. (Patel et al. 2014a), *Leptadenia reticulata* (Retz.) Wight & Arn. (Patel et al. 2014b), *Cadaba fruticosa* (L.) Druce (Lodha et al. 2015), *Blyttia spiralis* (Forssk.) D. V. Field & J. R. I. Wood (Patel et al. 2016a), *Tinospora cordifolia* (Willd.) Miers (Panwar et al. 2018), etc.

Figure 8. (a) *In vitro* multiplied shoots of *Cucumis* species; (b) Cucurbits under acclimatization and hardening phase in greenhouse

Micropropagation is the most widely accepted tool and exploited as a key component in 'integrated plant conservation' approach (Patel et al. 2020, Werden et al. 2020). Micropropagation of tree/woody species has great commercial importance, however, these are difficult to establish and propagate in vitro (Shekhawat et al. 2014c). The tree/woody species of stressed ecosystem usually possess recalcitrant contaminants (bacterial/fungal), phenolic compounds which hinder the explants to respond, especially harvested from the mature plants. There are several precautions through which these constraints could be overcame such as lopping of the mother plant in preceding season, season of explant collection, proper sterilization methods, anti-oxidant treatment prior to explant inoculation, etc. (Phulwaria et al. 2011, Patel et al. 2020). Using these and other such strategies, a number of desert/arid/semi-arid region-specific plant species have been successfully cloned/propagated at the Biotechnology Unit, Department of Botany, Jai Narain Vyas University, Jodhpur (Rajasthan). Some of them are *Tecomella undulata* (Sm.) Seem (Rathore et al. 1991), *Maytenus emarginata* (Willd.) Ding Hou (Rathore et al. 1992), *Zizyphus* species (Rathore et al. 1992), *Prosopis cineraria* (L.) (Shekhawat et al. 1993), *Capparis decidua* (Forsk.) Edgew. (Deora and Shekhawat 1995, Ram et al. 2022b), *Salvadora persica* Linn. (Phulwaria et al. 2011), *Acacia senegal* (L.) Willd. (Rathore et al. 2012), *Acacia nilotica* (L.) Del. ssp. *indica* (Rathore et al. 2014), *Salvadora oleoides* Decne. (Phulwaria et al. 2014), *Acacia nilotica* (L.) Del. ssp. *cupressiformis* (Rathore et al. 2015), *Punica granatum* cv. Jalore seedless (Dinesh et al. 2019), *Mitragyna parvifolia* (Roxb.) Korth. (Patel et al. 2016b, 2020), etc. Similarly, callus/somatic cell culture is a valuable tool not only for large-scale plant production but can also be employed for development of superior somaclonal variants, genetic transformation, genetic diversity enhancement and germplasm conservation (Patel et al. 2014b). Protoplast isolation, fusion and culture can be used for somatic hybridization or cybrids.

The maintenance of true-to-type nature of micropropagated plants is mandatory for upholding important traits of an elite genotype/cultivar, especially in commercial laboratories, tissue culture industry and for farmers (Bhojwani and Dantu 2013). The genetic homogeneity assessment of micropropagated plants has been done for several species such as *Psidium guajava* (Rai et al. 2012), *Celastrus paniculatus* (Phulwaria et al. 2013), *Salvadora oleoides* (Phulwaria et al. 2014), *Alhagi maurorum* (Agarwal et al. 2015), *Momordica dioica* Roxb. ex Willd. (Choudhary et al. 2017), etc. In contrast, genetic diversity is equally important for adaptability, long-term existence, to forecast the vulnerability towards extinction and survival of a species. DNA sequence based molecular markers (RAPD, ISSR, SSR, SCoT, CBDP, etc.) can efficiently be utilized in determining the genetic homogeneity as well as genetic diversity. The genetic diversity assessment of *Morinda tinctoria* population reveals the clonal plantation in the historical Mandore Garden, Jodhpur, as evidenced by the monomorphic banding pattern using RAPD and ISSR markers (Shekhawat et al. 2013). However, monomorphic pattern is supposed to be a challenge for any natural population of a species under the fragile ecosystem as these populations are more susceptible to ecological and climatic fluctuations.

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