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Review

The urgency of building soils for Middle Eastern and North African countries: Economic, environmental, and health solutions

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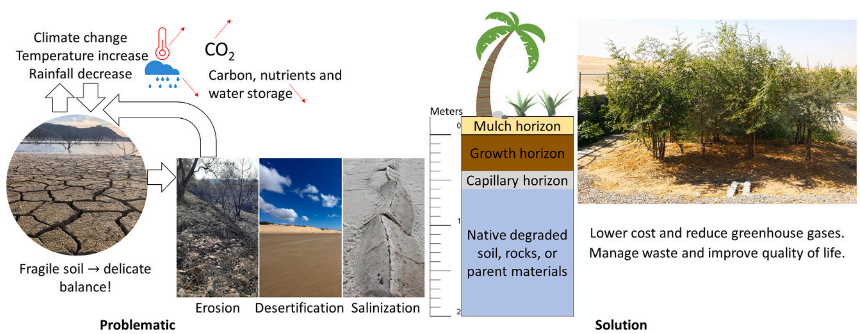
HIGHLIGHTS

- Soil degradation affects the life quality of the MENA region.
- Constructed soils can effectively align with soil reclamation efforts.
- Constructed soils are effective tools for waste management.
- A thoughtful implementation of soil engineering reduces costs and greenhouse gas emissions.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil degradation is a short or long ongoing process that limits ecosystem services. Intensive land use, water scarcity, land disturbance, and global climate change have reduced the quality of soils worldwide. This degradation directly threatens most of the land in the Middle East and North Africa, while the remaining areas are at high risk of further desertification. Rehabilitation and control of these damaged environments are essential to avoid negative effects on human well-being (e.g., poverty, food insecurity, wars, etc.). Here we review constructed soils involving the use of waste materials as a solution to soil degradation and present approaches to address erosion, organic matter oxidation, water scarcity and salinization. Our analysis showed a high potential for using constructed soil as a complimentary reclamation solution in addition to traditional ones. Constructed soils could have the ability to overcome the limitations of existing solutions to tackle land degradation while contributing to the solution of waste management problems. These soils facilitate the provision of multiple

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ecosystem services and have the potential to address particularly challenging land degradation problems in semi and dry climates.

1. Introduction

Land degradation is one of the greatest social-environmental challenges facing society. This process is associated with poverty, disease, political conflicts, decreased economic output, increased migration, food insecurity (Croitoru and Sarraf, 2010), and loss of biodiversity and associated ecosystem services (IPBES, 2018). Land degradation is closely related to the loss or degradation of productive soils (as the basis for life on earth). While soil degradation is a major issue worldwide (Borrelli et al., 2017; FAO, 2015), it is more intense under dry climates (Salhi et al., 2023) such as in the Middle East and North Africa (MENA) where soils are affected by salinization, erosion, and desertification. These problems are expected to increase over time (Climate and Environmental Change in the Mediterranean Basin, n.d.; Special Report on Climate Change and Land, n.d.), especially with predictions of a 25 % decrease in rainfall and a 2 °C increase in temperature by 2050 in region (Ragab and Prudhomme, 2002).

Land degradation is a short or long term process that limits or reduces ecosystem services through the loss of soil's physical, chemical, and/or biological qualities (IPBES, 2018). The process involves dynamic interactions between land characteristics, human activities, and climatic factors and has negative effects on important components of human well-being (e.g., poverty, food security threats, wars) (Barbier and Hochard, 2018). Key drivers of soil degradation include climate change, increased management intensity, urbanization, abandonment of rural areas, and poor soil management practices.

Soil degradation is caused by the removal of vegetation cover which exposes bare soils to raindrop impact (splash effect) and to direct evaporation (Marzen and Iserloh, 2021), increased frequency and intensity of droughts (especially pedological and ecological droughts), decreased net primary productivity (Pacheco et al., 2018), depletion of soil organic carbon and nutrient pools (Hsu and Dirmeyer, 2023), and loss of ecosystem resilience (Borrelli et al., 2017).

Erosion is the dominant mechanistic driver of land degradation, removing fine particles, nutrients, and organic matter from topsoil (Blanco-Canqui and Lal, 2008). This leads to decreases in soil thickness and thus water and nutrient reserves, reduced soil fertility, especially with water rill and wind erosion, and reduced plant growth, which increases soil susceptibility to further erosion. The rate at which soil erosion is occurring is often unsustainable. For example, in China and India, rates of topsoil loss by erosion are 30–40 times greater than soil regeneration rates (Pimentel and Kounang, 1998). Rates of regeneration are particularly slow in dry and semi-dry climates, and opportunities for active restoration are strongly limited by available water resources. In MENA, water demand for irrigation and industrial use is expected to increase by 50 % and supply is predicted to decrease by 12 % by 2050 (Droogers et al., 2012).

Salinization (i.e., the accumulation of salts in soil over time) decreases the ability of plants to take up water from the soil (Hassani et al., 2021). Any area where evapotranspiration exceeds water input is vulnerable to this process, which is exacerbated by poor quality (high salt content) irrigation and groundwater, wind erosion (aeolian transport of salt), and rock weathering (Rengasamy, 2006). Remediation of saline soils requires the use of large amounts of high-quality irrigation water to flush salts out of the soil profile. About 34 million ha of soil are affected by salinization, particularly in the MENA region (Negacz et al., 2022). Areas affected by salinization are expected to increase with climate change in South America, southern and western Australia, Mexico, the southwest United States, and South Africa (Hassani et al., 2021). An emerging contributor to salinization is the use of recycled wastewater for irrigation (Negm and Shareef, 2020). Due to water scarcity, over 40 % (up to 70 % in Israel) of treated wastewater generated in the MENA region is used for agricultural irrigation (Qadir et al., 2010). Unfortunately, this use increases soil salinity (secondary salinity processes), and in some cases permanently damages soil structure (Yasuor et al., 2020).

A relatively recently recognized driver of soil degradation is urbanization, which has accelerated in the MENA region in recent decades (Al-Mulali and Ozturk, 2015). Soil sealing, waste generation, freshwater consumption, and soil contamination have led to increased runoff rates and volumes and loss of vegetation in many cities (Alexandria, Cairo, Casablanca, Doha, Guelmim, Kuwait, Muscat, and Riyadh) (Loudyi and Kantoush, 2020).

Africa and Asia are facing a major issue of aridity (Li et al., 2021a) land degradation, affecting almost 23 million km^2 of each continent. Over the last two decades, significant changes such as population growth, economic development, and accelerated urbanization especially in Gulf countries have further worsened the most pressing environmental challenges shared throughout the MENA region. These challenges include water scarcity, depletion of arable land, ecosystem degradation, loss of biodiversity, poor waste management, and air and water pollution (Prăvălie, 2021). Additionally, earthquakes in Turkey and Syria and geopolitical conflicts in some countries have added to existing challenges and generated large amounts of waste. Land degradation and climate change worsen socio-economic imbalances by reducing the income of millions living in degraded rural areas (Prăvălie, 2021). This leads to poverty and inequality. By 2050, the global population will exceed 9 billion, and food production must increase by 60–70 %. However, land degradation and climate change will cause crop yield losses of 10 % globally and up to 50 % in some regions including MENA. This will further threaten global food security and social welfare.

The challenge of land degradation has led to a search for solutions that address the three components of sustainability (economics, environment, and equity). There is great interest in the use of Nature-based Solutions (NBS) as "actions which are inspired by, supported by or copied from nature" (Union, P.O. of the E, 2015) or Green Infrastructure (GI) as multifunctional networks of green spaces to address a wide range of environmental sustainability issues because of their ability to influence soil, water, climate, and biodiversity-related variables (Benedict and McMahon, 2006). The concepts of GI and NBS are now becoming widespread globally (Davies and Lafortezza, 2017; Pauleit et al., 2021) and there are any applications with an emphasis on urban areas (Pauleit et al., 2017; Pauleit et al., 2020).

Various techniques and efforts have been established to combat soil degradation in dry and semi-dry climates. These include improving plant selection and nursing, implementing plantation techniques for forestry restoration (Padilla and Pugnaire, 2006), and changing soil management practices in agricultural lands to encourage carbon conservation (Chakraborti et al., 2023; Tian et al., 2023). Additionally, altering the topography of the land to enhance water harvesting capabilities can also be effective (Rockström and Falkenmark, 2015). Despite all the efforts and previous techniques implemented, recovering vegetation in depleted and denuded dryland landscapes through natural succession processes is often a slow and almost impossible task, depending on the severity of degradation (Shackelford et al., 2021). Simply reducing livestock and wildlife grazing is often ineffective as degraded dryland environments can exhibit stability and resilience in undesired states. Seeding in dryland ecosystems presents a challenge, as most projects experience low germination and establishment success and high mortality in the development of seedlings to adult plants (Shackelford et al., 2021).

Soil sustainability and restoration success can be enhanced by the modification or construction specific soil horizons, yet this approach is seldom utilized or discussed. Use of constructed soils can enhance soil quality and reduce costs by utilizing available materials, including waste (Rokia et al., 2014; Deeb et al., 2020). Constructed soils can improve restoration success in harsh climates with smart design techniques and reduced cost.

In this review, we explore the potential for the use of constructed (engineered) soils as a solution for degraded lands in MENA. We first review the process of land degradation and introduce the concepts of NBS and GI. We then present results from a literature review focused on the use of engineered soils to prevent and mitigate land degradation under dry climates.

Currently, constructed soils are widely used in urban GI and NBS in the United States and Europe (Deeb et al., 2020; Rodríguez-Espinosa et al., 2021), yet the need for these soils is likely higher in regions such as MENA. In these regions, the need for NBS is not limited to cities as there is potential to apply this concept to the vast areas of degraded lands threatened by desertification. However, there is great uncertainty about the potential for using NBS and GI to address land degradation in arid regions such as MENA.

Although the majority of developing countries in MENA have an agriculturally focused economies with a high production of organic waste (around 67 % of their total waste) (North Africa and the Middle East through to the year 2050: towards a greater dependence on agricultural imports, n.d.). However, urbanization is increasing rapidly in these countries, generating construction and demolition waste (Chen et al., 2022). Landfill construction is costly for both developed and developing countries and requires long-term monitoring and management (Chen et al., 2022). Repurposing both organic and inorganic wastes to create constructed soils (Deeb et al., 2020) is a particularly appealing solution in these countries. The high organic content from agricultural waste is beneficial for retaining water in constructed soils and reduces the need for fertilizer, which saves money and improves water quality. The ability of constructed soils to support vegetation growth reduces the temperature in urban areas, thus improving microclimate and reducing the effects of greenhouse gases. Constructed soils that support food production could reduce the need to import food from rural to urban areas. In addition, there are economic savings from reduced needs to construct, transport waste to, or operate dump sites and to treat moist, organic-rich solid wastes that are unsuitable for thermal processing. Public health risks are reduced as uncollected waste can be gathered and used for soil construction. Less waste ends up at dump sites thus decreasing the chance of contamination of soil and water, and overall, fewer landfill sites will reduce air, soil, and water pollution. Providing a cleaner environment will result in less restoration costs, healthier residents, lower medical bills, and ultimately a higher quality of life (Deeb et al., 2020).

In this review, we first introduce the idea of constructed (engineered) soils as a solution for degraded lands in MENA, with a focus on the use of locally available waste materials. Further, we make recommendations for technical applications of these soils. Finally, we identify ecosystem services provided by constructed soils and discuss their economic value.

2. Materials and methods

2.1. Bibliographic search

Our research focused on designing engineered soils that are suitable for dry and changing climates. Due to limited references on this topic, only 3 articles in English, one report in French from Microhumus (French private company) and one report in Russian (Snoussi et al., 2024; Bhoobun et al., 2017; Smagin et al., 2018; Moreno et al., 2017) (Table 1) were found to address constructed soils on semi-dry and dry climates worldwide. We conducted bibliographic research starting from 1960 to January 2024 on Google scholar, web of science and other relevant scientific databases and appropriate cross-referencing to obtain literature to answer specific questions. These include: what challenges arise when restoring soils in dry climate areas? How do determine if restoration projects are successful? What are the best soil management practices in dry climates? What parameters are essential for soil functionality? Lastly, what is the most effective way to incorporate essential soil management principles into constructed soil design?

Structured searches were carried out with the following keywords: restoration, arid soil, soil formation, plant adaptation, constructed soil, engineered soils, desertification, salinization, food security, soil functions, dry land, soil erosion, management, recycling, landfill, and waste management. English, French, Germain, Arabic, and Russian language literatures were included. The review encompassed the use of constructed soils on arid, semi-arid, dry Mediterranean, mesic-Mediterranean, and irrigated lands (Rengasamy, 2006). Additional research was collected from private companies that have successfully used constructed soils in MENA that were contacted by the authors. The use of constructed soils for contaminated lands, green roofs, parks, tree-lined streets, green buffers, and urban farming was not included as these have been covered elsewhere (Deeb et al., 2020; Rodríguez-Espinosa et al., 2021).

3. Results and discussion

3.1. Constructed soils for arid and semi-arid regions

Design and use of constructed soils for dry climates requires the application of basic knowledge of soil pedogenic processes (e.g., horizon development (Séré et al., 2008)) and biotic/abiotic interactions (Deeb et al., 2016a; Deeb et al., 2017) to create a “soil” made by humans, or a mix of materials that could become a soil over time. In this review, we will use the term “constructed” or “built” soil. These soils are also referred to as “Technosols.”

Constructed soils can contain artifacts including waste materials and semi-natural materials such as sediments. These materials can be intentionally shaped in a variety of layers (Bhoobun et al., 2017) to provide a suitable environment for vegetation growth (Deeb et al., 2020) and other specific functions (Bhoobun et al., 2017; Smagin and Sadovnikova, 2016) (Fig. 1). There is particular interest in manipulating these layers to adapt to local climate conditions, especially precipitation, to maximize water harvesting.

3.2. What are the necessary steps to build healthy and functional soils?

Soil construction for a wide range of restoration plans requires several steps:

1. Diagnose and identify the type and degree of degradation, (salinity, erosion, loss of organic matter, contamination, sealing, etc.) topography, and climate conditions (Fig. 2). In addition, characterization of topography is essential for water harvesting. The potential for water collection is essential for the creation of restoration “hot spots” which are areas that have high provision of ecosystem services (Gilby et al., 2020). For example, building a soil at the bottom of a slope (Borrelli et al., 2021; Li and Pan, 2018; Li and Pan, 2020) instead of at the top takes advantage of the downslope movement and accumulation of water and fine materials (clay, carbon, or clay organic matter). This accumulation facilitates plant growth which creates a modified microclimate (shade, temperature reduction, etc.) that improves capacity and reduces costs by further improving conditions for plant growth. Another example could be to choose degraded lands located near agricultural lands to take advantage of plant residues and human resources. Cities could support hot spot areas as food waste is available, buildings can provide shelter from wind erosions, and the demand for ecosystem services is high in cities, building green spaces will be highly beneficial there.

Table 1
Large experiments in an arid area with constructed soil and modified surrounding areas for better water management.

Country	Project	Soil	Climate	Plants	Applied technic	Irrigation	Results
United Arab Emirates (Smagin et al., 2018)	Russian-Arab project "Green Wave" 1995	Arenosol	Extra-arid	Green lawn *Paspalum vaginatum* (plantation density 15–16 seedling/m^2)	Comparison of 4 treatments (1. control, 2. mulched topsoil with wood chips and granular sludge, 3. capillary barriers of 0.1 % polyacrylamide hydrogel, and 4. capillary barriers of 100 % garden peat).	Sprinkle (stationary irrigated system controlled automatically by watering timers)	In summer, water irrigation is reduced by 30–50 % in the soil with capillary barriers (3 and 4 treatments). Biomass of lawns in treatments 3 and 4 exceeded by 1.5–2 times control and mulching treatments.
Qatar near Doha (Smagin et al., 2018)	AridGrow 2005	Calcisol contains big amount (50 %) of limestone	Extra-arid	Green lawn *Paspalum hybrid*	1. The upper horizons were cut off with special machines and equipment. The excess of stony inclusions is removed by screening. 2. Only sifted soil (sand) is used. 3. Lime stones were removed and stored separately, then used in deep horizons of the soil in a 10–20 cm thick layer to create a capillary barrier (to avoid secondary salinization). 4. For the topsoil 1. local sifted sandy soil (Arenosols) was compared to the sand mixed with 5–10 % natural organic soil materials produced from mechanically activated peat and sapropel. 5. Before planting, the topsoil was cleaned from soluble salts and achieved a normal salinity level (EC = 6–8 dS/m).	Sprinkling	Protection of the topsoil from secondary salinization. High productivity of green lawns. Reduction of water irrigation when organic matter was added.
Bahrain (Smagin et al., 2018)	AridGrow 2004–2005	Arenosol	Extra-arid	Alfalfa, onions, tomatoes, cucumbers	Capillary barriers made of peat-sapropel soil modifier in the upper 10-cm thick layer mixed to soil (5 to 10 % volume ratio), and compared to application of chicken manure and control (no adding of organic matter)	Flood irrigation	The efficiency of water use (calculated as the ratio of productivity to the amount of irrigation water (kg/m^3)) was the highest (6–7 kg/m^3) in the case of the peat-sapropel soil modifier, followed by chicken manure (4 kg/m^3); and finally, untreated control (3 kg/m^3).
Jordan (Smagin et al., 2018)	ARICAD (Arab International Company for Agricultural Development) 2008	Loamy sand soil	Semi-arid	Potatoes	Peat-sapropel soil modifier "AridGrow" was applied in different quantities in the plantation root depth layer, and was then covered with the soil in the site (loamy sand). This treatment was compared to chemical fertilizer NPK (traditional method)	Point drip	Increase efficiency of irrigation by avoiding preferential water flows "wetting bulb" or an ever-growing zone of high humidity under the dropper. Peat sapropel soils block the spreading of moisture zoon and reduce water irrigation by 50 % compared to the use of chemical fertilizer. Higher biomass production compared to the use of chemical fertilizer.
Emirate	Emirate/ French Project 2012	Sandy soil	Extra-arid	Trees	15 plots with sandy soils mixed with different	Point drip	The irrigation was reduced by 50 % after

(continued on next page)

Table 1 (*continued*)

Country	Project	Soil	Climate	Plants	Applied technic	Irrigation	Results
					ratios of dehydrated sewage sludge (DSS) at the topsoil of 6.5 * 3 m plot as follow: (sandy soil alone (control) + sand with 45 L/m^2 DSS + sand with 100 L/m^2 DSS sand with 200 L/m^2 DSS + sand with 100 L/m^2 DSS and 9 L compost covered with 5 cm mulch) * 3		2 years and was stopped in the third year. Trees survive under SSD and compost plots compared to control. Trees grow very well only when compost and mulch were used in the first years.
17 km northwest of the city of La Paz, Baja California Sur, Mexico at the southern limit of the Sonoran Desert (Moreno et al., 2017)	Research project supported by the Bashan Institute of Science, USA		Arid with mean annual precipitation of 180 mm	4 species of plants were planted in 2004: the legume trees, mesquite amargo *Prosopis articulata*, yellow palo verde *Parkinsonia microphylla* (Torr.), blue palo verde *Parkinsonia florida*, and the giant cardon cactus *Pachycereus pringlei*.	Trees in 6 independent field experiments were grown individually or in a combination of a legume tree and Cardon cactus and were originally treated with plant growth-promoting bacteria, arbuscular mycorrhizal fungi, or small amounts of cattle compost, or a combination of all treatments.	Supplement irrigation to achieve the maximum natural annual rain300 mm amounts was applied with frequencies according to the average monthly precipitation equivalent to 10–20 mm of rain per month.	The best survivor was the cardon cacti and, to a lesser extent, the legume tree mesquite Amargo. After 11 years, a combination of a legume tree with cardon cactus, while detrimental to the legume, highly increased the chances of the cactus surviving and growing. The biotic (plant growth-promoting bacteria, arbuscular mycorrhizal fungi) and compost treatments, enhanced the initial establishment of the plants in 2004, but their positive benefits on the plant were negligible 11 years later

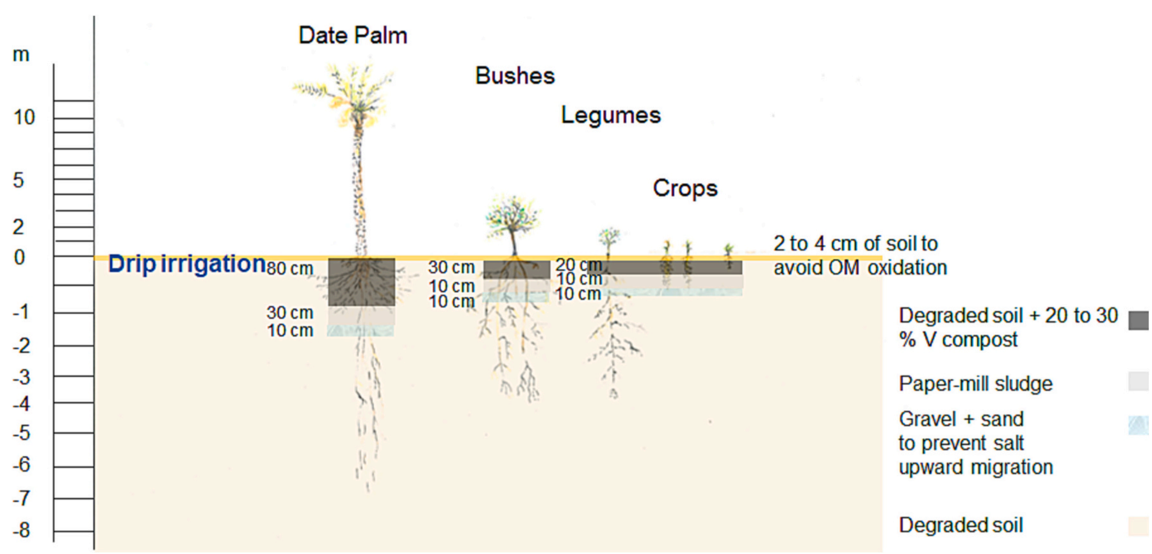

Fig. 1. Examples of constructed soil in an arid environment (root system form, and depth adapted from Kirschner et al., 2021). The diagram shows the relationship between the choice of plants and waste. Organic waste (compost, paper mill sludge) should be avoided on the surface to prevent hydrophobicity and rapid mineralization. The topsoil could be covered with gravel, straw, etc. The depth of the horizons and the amount of compost to add depends on the plant species. The integration of specific impermeable horizons could make it possible to regulate the capillarity of the soil by forming barriers (using gravel, and rocks) interrupting the hydraulic connection and thus avoiding salinization. The choice of plant communities and their combination must be considered because it can provide shade and reduce the effect of heat and wind (often loaded with sand). The development and interaction of root systems of different plant species can provide complete soil coverage and thus protect it from erosion, carbon deoxidation, and water evaporation. Finally, a suitable irrigation system (localized drip irrigation, water collection with buffer zones) will optimize irrigation water needs.

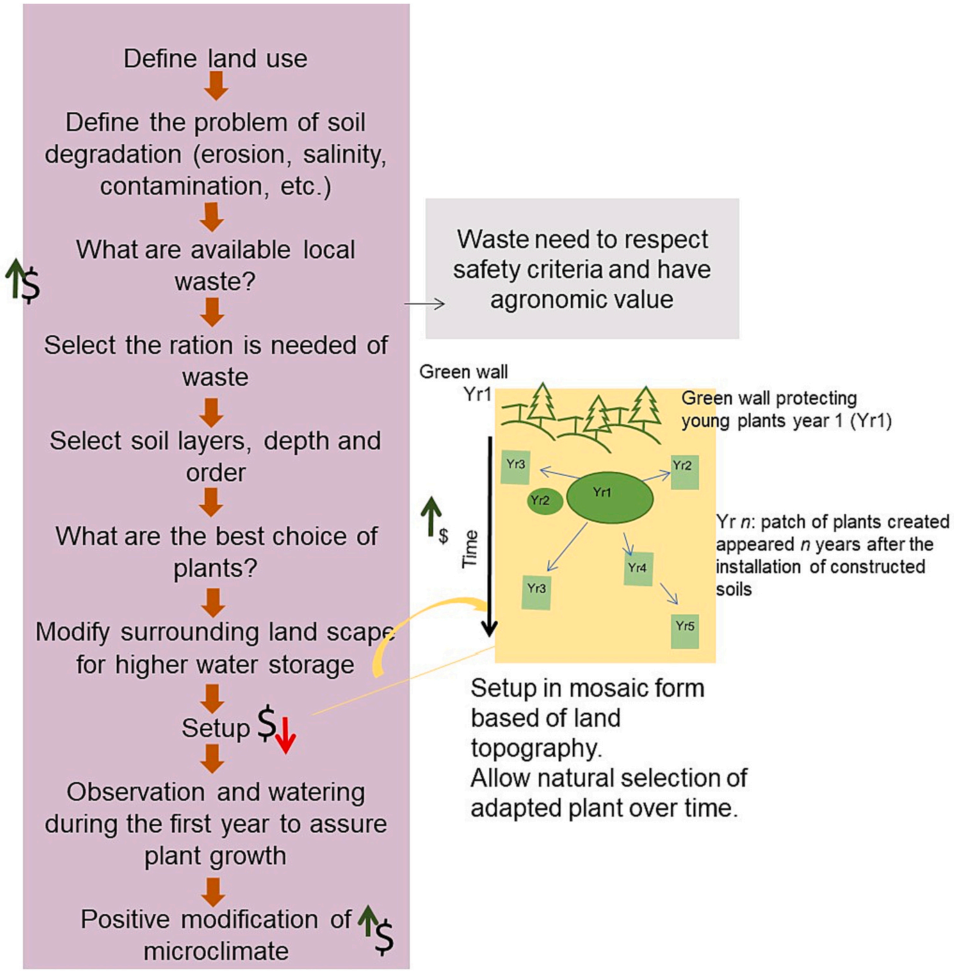

Fig. 2. Steps to build soil under dry climate conditions. Where: ↑$ potential of high cost, and ↓$ lower cost.

2. Search for locally available waste and evaluate its agronomic and hydric characteristics. This step could include long-term encouragement of composting practices while discouraging burning plant residues, as well as developing markets for plant waste resale (Ayilara et al., 2020). The main criteria for waste selection (Deeb et al., 2020) include: waste should be nontoxic, not difficult to handle, have agronomic value, and be available. Waste materials that contain invasive plants should be avoided.
3. Creating new soil layers and identifying their depth and functionality. Our analysis suggests that three horizons need to be included in constructed soils in dry climates:

3.2.1. *Mulching horizon*

Mulching is an application of organic (e.g., animal and plant residues), inorganic (e.g., sand, gravel, concrete, polyethylene plastic mulch), or mixed materials as a layer to cover or coat the soil surface. A mulching horizon is important for reducing water evaporation, salt accumulation erosion and the loss of organic matter by oxidation in the topsoil layers. Mulching has been shown to provide multi-beneficial advantages in agricultural soils (Iqbal et al., 2020) and in restoration projects (Wang et al., 2017). These benefits include decreased soil evaporation and increased soil moisture (Kader et al., 2019), regulation of soil temperature in both very hot (Kader et al., 2019) and cold (Prosdocimi et al., 2016) climate conditions, little to no loss of soil organic matter by oxidation (Li et al., 2021b) or soil erosion (Prosdocimi et al., 2016), enhanced soil biodiversity (Leclercq-Dransart et al., 2020) and fertility (Li et al., 2004), reduction of water runoff or flooding effects, especially after long period of drought, better control of salt stress (Li et al., 2023), better seedling establishment, even in sandy soils (Al-Mulali and Ozturk, 2015), mitigated environmental stresses (Shah et al., 2022), increased chances of restoration success in semi dry climates (Wang et al., 2017; Fehmi and Kong, 2012), and even in contaminated land (Leclercq-Dransart et al., 2020). Mulching can also be beneficial in post-fire scenarios. It can help improve soil conditions and reduce sedimentation, while also reducing dust transport, nutrient loss, and soil productivity decline. By integrating nearby potential mulching materials, such as certain organic matter, sustainable practices can be implemented to improve the success of land restoration projects.

It is important to avoid the following mulching practices:

- Plastic mulching materials that have been shown to control the soil environment and increase crop yield in temperate climates (Abbate et al., 2023) are not recommended in the MENA region as they are prone to decompose under high temperature, and their fragments add an environmental risk of contamination by microplastic (Qi et al., 2020). In addition, removing plastic mulches adds extra labor costs, especially after restoration efforts. Perhaps most importantly, in the MENA region, plastic mulching is likely to raise soil temperatures to dangerously high levels for roots and other soil organisms (Wu et al., 2020).
- Compost and municipal waste compost at the top layer: Several studies have shown the importance of composting, including municipal waste composting, for mulching (Miyasaka et al., 2001; Agassi et al., 2004; Erhart and Hartl, 2003). However, compost can become hydrophobic and wear away easily under high temperatures

(Voelkner et al., 2017; Deeb et al., 2016b). Additionally, organic waste should not be directly added to the topsoil to avoid exposure to aerobic decomposition.

- Burnt waste: A study (López-Urrea et al., 2020) showed that using burnt organic waste at the soil surface reduces water evaporation, but could contribute to microplastic contamination and hydrophobicity. Dehydrated organic matter should be avoided in dry climates because it can become hydrophobic (Rajhi et al., 2023; Naasz et al., 2008).
- It is better to avoid using animal waste, such as manure, in the mulch layer due to its high cost and potential to attract pests. This should be used in the growth layer.

Mulch should be made from the nearest available materials to reduce cost.

- Waste materials that have been used as a mulching layer include paper waste (Haapala et al., 2014), material from sawmills, material from wood furniture manufacturers such as bark sawdust and wood mulch (Agassi et al., 2004), and chipped wood (Barthes et al., 2010), maize straw, fodder grass, tree leaves (Hu et al., 2018), plant waste (Salem et al., 2021) (Yang et al., 2022), seaweed (Rajhi et al., 2023) and olive mill wastewater. Using gravel and rocks (stone mulch) is a cheap and sustainable approach as some soils in dry and semi dry climates contain gravels and rocks (Ramón Vallejo et al., 2012).
- After harvesting, plant residues make an excellent material to use as a cover for constructed soils These materials improve soil structure (Deeb et al., 2021) and reduce evaporation. Using available plant residue from nearby farms can increase yield (Issoufou et al., 2020) and allow the farmer to participate in the economic cycle (Fig. 3).

3.2.2. Growth horizon

This horizon is created by mixing different types of organic waste with available mineral waste or native soil on site to facilitate fast plant growth. The ratio of organic matter to other materials will vary based on land use and availability. The cost of constructing the horizon can be reduced by combining organic and mineral waste with specifically adapted plants (Deeb et al., 2020). The amount of organic waste present has a strong impact on water storage (Deeb et al., 2016b); however, many native plants do not need a high level of organic matter. A compost content of 10 % volume at a depth of 30 cm may be sufficient. If the goal is crop production, the content may need to increase to 20 or 30 %. The depth of the horizon could vary depending on the type of vegetation, such as trees, shrubs, or grasses (Fig. 4). Small amounts (5–10%V) of expensive materials such as biopolymers and sugar-based biopolymers can be added to the mix. These materials have shown high potential to reduce soil erosion (Chang et al., 2015), strengthen soil structure (Jang, 2020), increase water storage, control water infiltration (Jang, 2020; Ayeldeen et al., 2016), and promote plant growth (Ni et al., 2023). Biochar, a carbon-rich material produced from biomass, can improve soil physical/chemical properties (Sohi et al., 2010), increase plant productivity (Song et al., 2022; Thomas and Gale, 2015), and mitigate climate change through carbon sequestration and increased plant C uptake (Amoah-Antwi et al., 2020). Evidence of greater water holding capacity (Smagin et al., 2022) and reduced infiltration (Rodriguez-Franco and Page-Dumroese, 2021) suggests that these materials have the potential to improve the productivity of dry and semi dry environments if used in the growth horizon (Smagin et al., 2019). There is limited research on identifying the best characteristics of biochar for dry and semidry climates. However, it is advisable to avoid biochar with high salinity. It's important to consider project size, budget, and availability when selecting and managing available waste materials for each horizon.

3.2.3. Capillary horizon

Under dry conditions water evaporates from the soil surface, water and salt from the subsurface are drawn towards the surface by capillary flow (Lu and Likos, 2004; Li et al., 2018), and salts are left behind. In the absence of flushing precipitation or irrigation, salt accumulation eventually inhibits plant growth (Smagin, 2021). To combat this process of human-driven "secondary salinization," soils can be constructed with either a layer of coarse gravel to block capillarity or with impermeable layers that retain water and thus inhibit (either completely or partially) upward capillary flow and prevent salt accumulation in surface soils (Lu and Likos, 2004; Li et al., 2018; Smagin, 2021).

Imperfect capillary barriers are usually formed from natural and synthetic polymeric materials (mechanically activated peat, peat-sapropel soil modifiers, composts, sewage sludge, synthetic hydrogels,

Horizon	Depth	Services	Example of waste
Mulch	2-5 cm	Mulch application to protect topsoil, avoid water loss by evaporation and organic matter oxidation, reduce topsoil temperature, and provide habitat and nutrients to soil organisms.	Fresh plant residues, rocks, wood industry waste, newspapers, sand
Growth	30-50 cm	The manufactured mixture serves as the primary rooting environment, providing high fertility and water retention for rapid plant growth and establishment.	A mixture of compost, animal waste (such as blood and bones), sewage sludge, and polymers combined with topsoil.
Capillary	15-25 cm	Cut the water movement from subsoils to the topsoils to avoid salt accumulation and allow good infiltration.	Stones, rocks, paper mill sludge, sands
Native degraded lands	No required depth	Physical plant support.	No need to use any waste

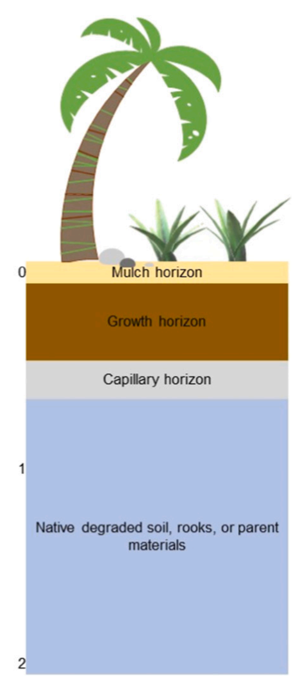

Fig. 3. Illustration on soil horizons in constructed soils for MENA region.

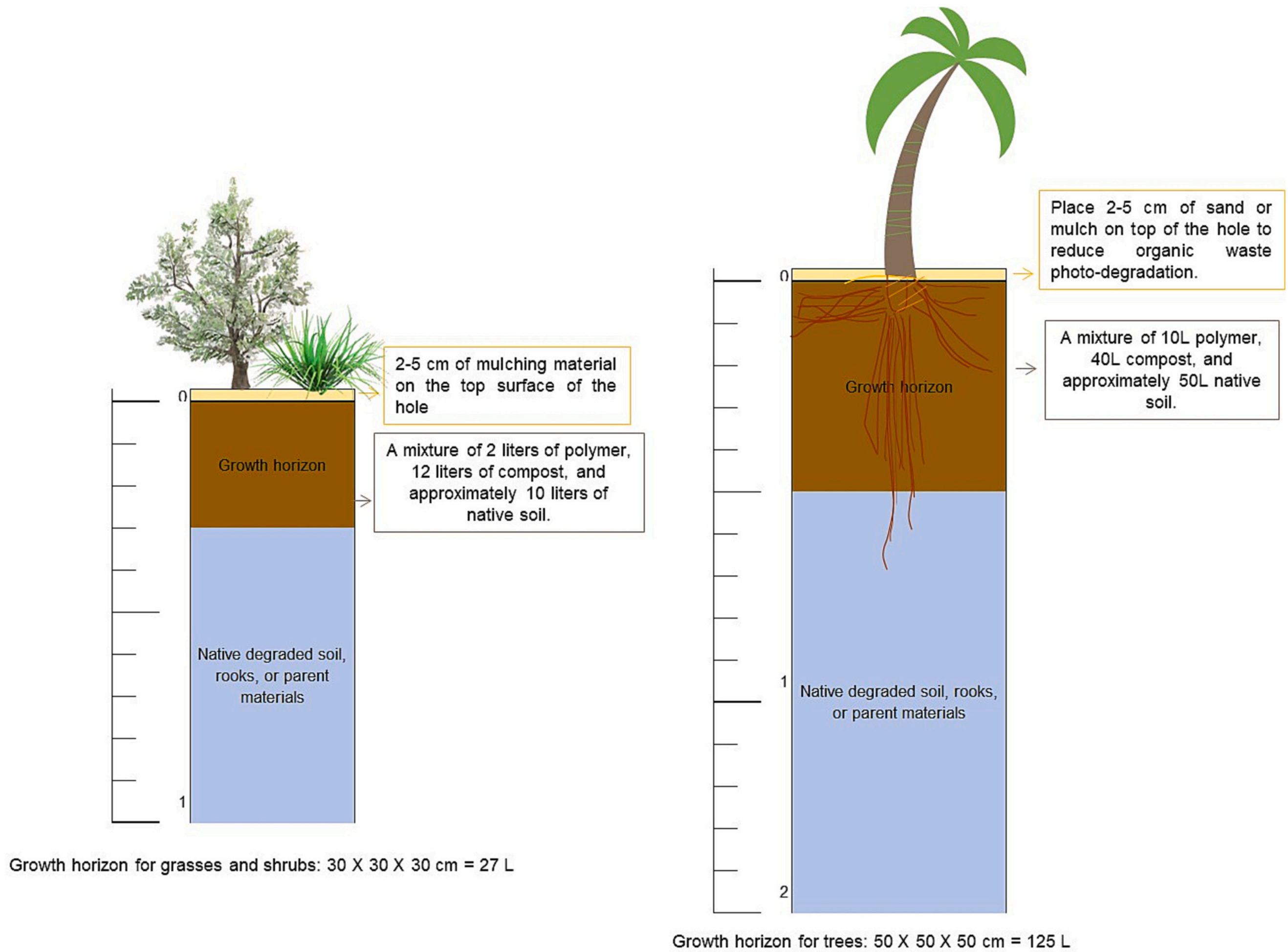

Fig. 4. Here is an example of the depth and mixture of growth horizon for trees and shrubs. Soil profile measured by meter.

etc.) with high dispersity and water retention, and reduced hydraulic conductivity. The physical parameters of such barriers, that is, the doses and the optimal depth of placement of soil conditioners, options for applying materials to the soil (in a separate layer or mixing), irrigation methods, and selected crops are determined using computer models of energy and mass transfer in the "soil-plant-atmosphere" system, for example, HYDRUS-1D or HYDRUS-2/3D (Smagin and Sadovnikova, 2016). It is necessary to experimentally evaluate the water retention curves and the saturated hydraulic conductivity of the soil-modifying materials relative to the original soil, for example, using a centrifugal method to separate water from the soil (Smagin and Sadovnikova, 2016).

Perfect barriers with complete blocking of the capillary flow are formed from coarse-dispersed materials (sorted from crushed stone, limestone, expanded clay) and/or hydrophobic impregnations and films (hydrocarbon or silicone hydrophobized, water-repellent geotextile). These materials do not have water-retaining curves, so a different approach is required for the design of these barriers. For these materials, the thermodynamic concept of water retention and the physical quality of soils (Smagin, 2021), which considers the limiting (critical) states of equilibrium between various physical forces (molecular, ion-electrostatic, capillary, gravitational) affecting water in two-phase and three-phase physical systems of soils and soil conditioners are considered. A basic rule for the design of perfect barriers is that the depth of the barrier (subsoil screen) should not exceed the maximum height of the capillary rise in the upper soil layer cut off by such a barrier (Smagin, 2021). Otherwise, a perfect capillary barrier instead of a water accumulator for topsoil, will become a drainage collector. The critical parameter of the maximum height of capillary rise can be estimated directly by experiment or indirectly by a model (Smagin, 2021) driven by information about particle size distribution, bulk density, solid phase density, soil wettability, and adsorbed water content (Fig. 5 example of constructed soil to avoid soil secondary salinization).

Capillary barriers can have 1, 2, or 3-dimensional architectures, depending on the direction of capillarity blocking, vegetation placement (solid cover, local plantings), and type of irrigation (sprinkling, flooding, furrow irrigation, jet, drip irrigation) (Smagin, 2021; Al-Maktoumi et al., 2015).

4. Plant selection

Choosing the right plants for constructed soils is crucial. The plants should be able to thrive in the dry climate and have a root system that increases water storage in the soil. It is wise to consider native plants as studies have emphasized their importance under degraded ecosystem conditions. For instance, study (Ohte et al., 2003) showed that exotic plants could lead to groundwater shortages whereas indigenous tree species conserve water. In addition, researchers (Bremer and Farley, 2010) argue that biodiversity was higher when native plants are used compared to exotic plants in degraded lands. However, strategies based on native plants can be unsuccessful (Grantz et al., 1998) due to the reduction of water availability with climate change.

Identifying which species are most effective for restoration projects can be a challenge, as it varies depending on the region and the project. However, a model created in 2021 analyzed restoration seeding outcomes across 174 sites on six continents, with 594,065 observations of

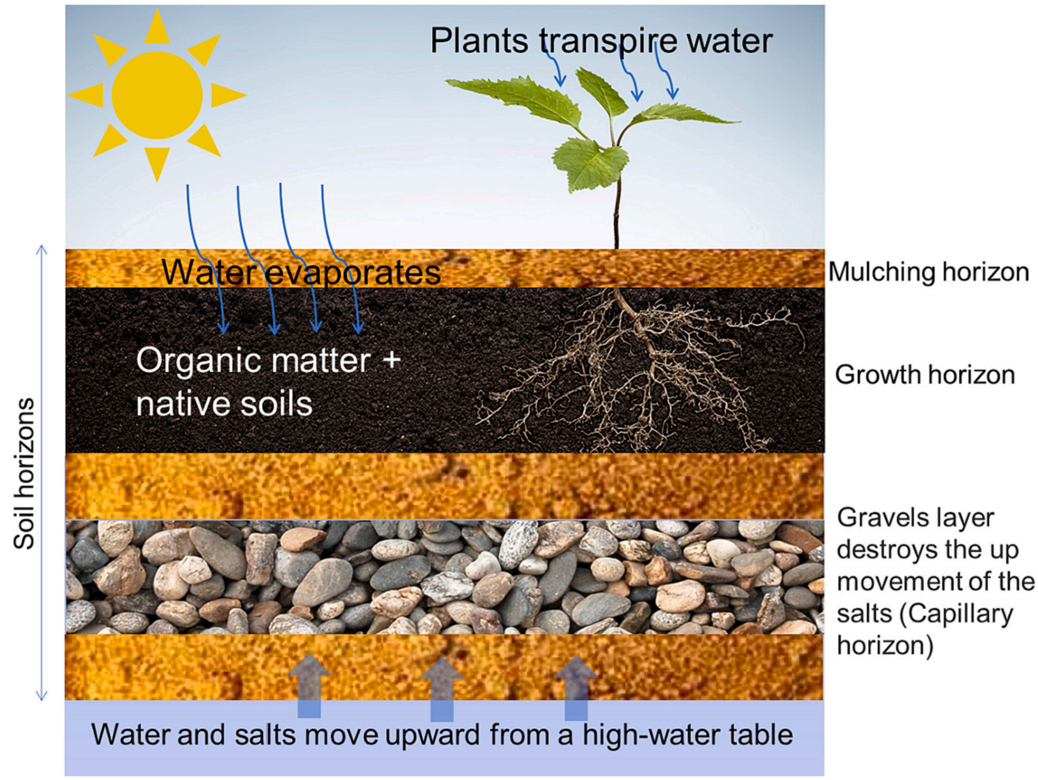

Fig. 5. Diagram of a constructed soil to prevent secondary soil salinity.

671 plant species (Shackelford et al., 2021). The model found that the species identity accounted for 30 % of all variation in success (Shackelford et al., 2021). This suggests that certain taxonomic groups may have traits that influence plant growth and survival in arid ecosystems. For example, some species may reduce water loss or improve local conditions. Species from the genus Bromus (*Poaceae*), Acacia (*Fabaceae*), and Centaurea (*Asteraceae*) showed high average success across species (Shackelford et al., 2021). Therefore, it is essential to carefully choose the appropriate species and integrate these selections into the soil engineering design to increase the success of restoration projects.

Biotic interactions are a crucial element when soil is constructed (Deeb et al., 2016a; Deeb et al., 2017). A variety of parameters need to be considered when plants are selected: shading to reduce heat and wind effects, shoot and root system development (Kirschner et al., 2021) and their interactions to allow a complete covering of the soil and protect it from erosion, carbon oxidation, and water evaporation (e.g., Fig. 1). Overall, the development of a variety of root systems would provide a better sharing of available water (as it would be taken from different soil horizons), increase plasticity in water uptake (Kirschner et al., 2021), increase conductivity, and improve soil structure (Deeb et al., 2016c) as well as water storage (Deeb et al., 2016a). Biotic interactions create a favorable ecosystem for roots, improve microhabitats, and reduce plant mortality during extreme heat waves (Saccone et al., 2009). In addition, plant interactions improve resistance and resilience under different degrees of drought stress (moderate to intense) (Volaire et al., 2014) in Mediterranean areas, reduce emerging disease, and vegetation losses (Keesing et al., 2010), increase community stability, soil nutrient availability, and carbon storage (Keesing et al., 2010). It is imperative to note that the efficacy of organic matter mixed with soil in the rhizosphere environment diminishes after some years of plant establishment. As a result, the role of compost must be replaced with biotic interactions to ensure optimal results. Study found that plant survival in degraded deserts after 11 years was highly dependent on neighboring plants, while the composting effect was dispersed (Moreno et al., 2017).

Observation and watering in the period just after planting (both direct seeding and seedling) is critical to avoid plant mortality and poor growth. Once plant development starts, less observation and watering are required as plants also begin to positively affect their microclimate (von Arx et al., 2013). The use of runoff water harvesting systems, which are widely described in the literature (Van Rensburg et al., 2012). May be useful for reducing irrigation costs.

To save costs and allow for flexibility during the application and planting process, it is better to consider using an open mosaic style (Radeloff et al., 2000) rather than directly establishing constructed soils on a large scale due to high costs. Establishing patches will reduce costs and the established patches facilitate colonization of unplanted areas with constructed soils. However, a patch mosaic strategy alone could fail due to climate change effects. Choosing plant species with high drought tolerance may overcome this problem, allowing natural filtering of species, leaving only the more stress-tolerant species to grow (Hulvey et al., 2017).

4.1. What ecosystem services are provided by constructed soils in Mediterranean, semi-arid, and arid areas?

Several case studies, in a variety of land uses (Table 1) have shown that constructed soils enhance water storage, reduce the amount of water needed for irrigation, enhance food production, prevent erosion and salinization, promote microbial biodiversity, and increase plant production and survival (Smagin et al., 2018). Additionally, in urban contexts, constructed soils have been shown in the Europe and the United States to reduce costs, provide solutions for waste management, reduce greenhouse gases, and improve quality of life (Deeb et al., 2020).

It is important to highlight that the effects of organic matter added when soils are constructed will decline over time (Moreno et al., 2017). However, the idea behind constructed soils is to provide a sustainable environment for plant establishment and growth that will replace the initially added organic matter. Additional irrigation in the first few years of establishment is helpful to avoid plant mortality (Chávez-García and González-Méndez, 2021), but can be costly, especially in semi-arid ecosystems (Liu et al., 2020) and is areas with extreme degradation (desert). However, identifying priority areas and application of small patches can reduce costs. In addition, using waste materials can reduce or even entirely balance establishment costs.

Ultimately, the cost of soil degradation is higher than the cost of land restoration. Constructing soils using waste materials could be a cost-effective solution that recycles a large quantity of waste, bringing these materials back into the economic cycle. Over time, the ecosystem services provided by constructed soils will increase as growing vegetation improves microclimate conditions, which improves many ecosystem services. Constructed soils should be considered to be an important component of nature-based solutions for reducing greenhouse gases emissions and mitigating climate change (Ruiz et al., 2023).

4.2. What are the limitations of using constructed soils as a restoration solution in MENA and how can we encourage their widespread application?

Solid waste management is a major challenge in the MENA region, causing various problems for local authorities. The use of constructed soil can be an effective solution to a significant portion of this problem, as it avoids the need for land filling and subsequent treatment (Deeb et al., 2020). However, there are several challenges in the use of waste materials in corporate application of constructed soils. This application requires sufficient planning of waste management, better collection services, composting, financing, and better communication between different sectors to allow for the reuse of waste from the nearest disposal site (Negm and Shareef, 2020). These challenges arise from political factors and the decentralized nature of waste management. Reusing this waste in constructed soils can transform it from being a waste to a valuable resource (Deeb et al., 2020), but its large-scale implementation requires better integration of the private sector. Providing relevant information and training to enable such practices is crucial to this information (Ayilara et al., 2020).

There is also a strong need to establish clear environmental regulations to ensure the safe reuse of waste in food production. If the waste poses any risk of contamination, it should not be used in constructed soils intended for cultivation (Deeb et al., 2020). Therefore, there is a need to create laws and regulations that govern waste management practices, promote recycling, encourage the separation of waste, and support energy and materials recovery. These regulations should also empower communities to have greater control over waste management. This requires a significant effort from scientific, social science, and economic fields to create a legal environment for better application. A comprehensive development strategy requires investments that improve the livelihoods of affected populations and regions and facilitate out-migration in severely impacted areas.

This study proposes a solution for restoration in Mediterranean, semi-arid, and arid climates in the MENA area for the first time with limited examples of applications provided in the literature (Table 1). Further research is needed to evaluate its direct application.

5. Conclusion

Controlling and restoring dryland degradation is challenging. There is a great need to find cost-effective, scalable, and reliable solutions to restore degraded land in many areas of the world (Cook-Patton et al., 2021; Adepoju, 2021) including the MENA region. Our analysis suggests that that building soils is an important component of efforts to address both desertification and salinization problems in the MENA region. Building soils has great potential to reduce restoration costs under both severe and more moderate levels of degradation.

Our analysis also highlights key research needs related to the use of constructed soils in the MENA region. There is a strong need for evaluate the wide variety of waste products that are available in the region for their suitability for use in constructed soils in terms of application on large scales, long-term performance of constructed soils, and socio-economic benefits from their use. There is also a strong need for research on the soil ecology, pedology, and biotic/abiotic interactions in constructed soils. This research could be an important step towards improving restoration efforts across the MENA region.

CRediT authorship contribution statement

Maha Deeb: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Andrey Valentinovich Smagin:** Writing – review & editing, Validation, Methodology. **Stephan Pauleit:** Writing – review & editing, Funding acquisition. **Olivier Fouché-Grobla:** Writing – review & editing. **Pascal Podwojewski:** Writing – review & editing. **Peter M. Groffman:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maha Deeb, Stephan Pauleit reports financial support, travel, and writing assistance were provided by German Research Foundation. Andrey Valentinovich Smagin reports financial support and writing assistance were provided by Russian Science Foundation. Maha Deeb reports a relationship with Technical University of Munich that includes: consulting or advisory, funding grants, and speaking and lecture fees. Andrey Valentinovich Smagin reports a relationship with Lomonosov Moscow State University that includes: employment and funding grants. This work is original research written by researchers from different origins and rich academic backgrounds to explore ways to construct soils by using local materials to overcome resource limitations and improve human quality of life. The analysis is focused on particularly challenging land degradation contexts in the Middle East and North Africa. All the co-authors contributed to this review through years of expertise in the Middle Eastern and North African Countries. The authors have no conflicts of interest to declare and there is no significant financial support for this work that can influence its outcome. We declare that this manuscript has not been published before, in whole or in part, and is not currently being considered for publication elsewhere. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

Our motivation for writing this review article is to extend a hidden message of peace to all those who have lost a loved one because of war. The conflict that we have witnessed in the Middle East has led to many tragic deaths, often because of resource limitations (water and soil) or differences in religious beliefs that have not been accepted. We strongly believe that it is important to acknowledge these issues and work towards finding a peaceful resolution that can avoid further loss of life. This is why we have dedicated this research which summarizes a long journey of research worldwide to exploring ways to construct soils by using local materials to overcome resource limitations and improve human life quality.

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References

Abbate, C., Scavo, A., Pesce, G.R., Fontanazza, S., Restuccia, A., Mauromicale, G., 2023. Soil bioplastic mulches for agroecosystem sustainability: a comprehensive review. Agriculture 13, 197. https://doi.org/10.3390/agriculture13010197.

Adepoju, P., 2021. Restoring Africa's degraded land has economic and environmental benefits. Afr, Nat. https://doi.org/10.1038/d44148-021-00115-z.

Agassi, M., Levy, G.J., Hadas, A., Benyamini, Y., Zhevelev, H., Fizik, E., Gotessman, M., Sasson, N., 2004. Mulching with composted municipal solid wastes in Central Negev, Israel: I. Effects on minimizing rainwater losses and on hazards to the environment. Soil Tillage Res. 78, 103–113. https://doi.org/10.1016/j.still.2004.02.021.

Al-Maktoumi, A., Kacimov, A., Al-Ismaily, S., Al-Busaidi, H., Al-Saqri, S., 2015. Infiltration into Two-Layered Soil: The Green–Ampt and Averyanov Models Revisited. Transp. Porous Media 109, 169–193. https://doi.org/10.1007/s11242-015-0507-8.

Al-Mulali, U., Ozturk, I., 2015. The effect of energy consumption, urbanization, trade openness, industrial output, and the political stability on the environmental degradation in the MENA (Middle East and north African) region. Energy 84, 382–389. https://doi.org/10.1016/j.energy.2015.03.004.

Amoah-Antwi, C., Kwiatkowska-Malina, J., Thornton, S.F., Fenton, O., Malina, G., Szara, E., 2020. Restoration of soil quality using biochar and brown coal waste: a review. Sci. Total Environ. 722, 137852 https://doi.org/10.1016/j.scitotenv.2020.137852.

Ayeldeen, M.K., Negm, A.M., El Sawwaf, M.A., 2016. Evaluating the physical characteristics of biopolymer/soil mixtures. Arab. J. Geosci. 9, 371. https://doi.org/10.1007/s12517-016-2366-1.

Ayilara, M.S., Olanrewaju, O.S., Babalola, O.O., Odeyemi, O., 2020. Waste management through composting: challenges and potentials. Sustainability 12, 4456. https://doi.org/10.3390/su12114456.

Barbier, E.B., Hochard, J.P., 2018. Land degradation and poverty. Nat. Sustain. 1, 623–631. https://doi.org/10.1038/s41893-018-0155-4.

Barthes, B.G., Manlay, R.J., Porte, O., 2010. Effects of ramial wood amendments on crops and soil: a synthesis of experimental results. Cah. Agric. 19, 280–287.

Benedict, M.A., McMahon, E.T., 2006. Green Infrastructure: Linking Landscapes and Communities, Illustrated edition. Island Press.

Bhoobun, B., Vasenev, V.I., Smagin, A.V., Gosse, D.D., Ermakov, A., Volkova, V.S., 2017. Hydrophysical properties of substrates used for Technosols' construction in Moscow Megapolis. In: International Congress on Soils of Urban. Industrial, Traffic, Mining and Military Areas (Springer), pp. 260–266.

Blanco-Canqui, H., Lal, R., 2008. Soil and water conservation. In: Blanco-Canqui, H., Lal, R. (Eds.), Principles of Soil Conservation and Management. Springer, Netherlands, pp. 1–19. https://doi.org/10.1007/978-1-4020-8709-7_1.

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., et al., 2017. An assessment of the global impact of 21st century land use change on soil erosion. Nat. Commun. 8, 2013. https://doi.org/10.1038/s41467-017-02142-7.

Borrelli, P., Alewell, C., Alvarez, P., Anache, J.A.A., Baartman, J., Ballabio, C., Bezak, N., Biddoccu, M., Cerdà, A., Chalise, D., et al., 2021. Soil erosion modelling: a global review and statistical analysis. Sci. Total Environ. 780, 146494 https://doi.org/10.1016/j.scitotenv.2021.146494.

Bremer, L.L., Farley, K.A., 2010. Does plantation forestry restore biodiversity or create green deserts? A synthesis of the effects of land-use transitions on plant species richness. Biodivers. Conserv. 19, 3893–3915. https://doi.org/10.1007/s10531-010-9936-4.

Chakraborti, R., Davis, K.F., DeFries, R., Rao, N.D., Joseph, J., Ghosh, S., 2023. Crop switching for water sustainability in India's food bowl yields co-benefits for food security and farmers' profits. Nat. Water 1–15. https://doi.org/10.1038/s44221-023-00135-z.

Chang, I., Prasidhi, A.K., Im, J., Shin, H.-D., Cho, G.-C., 2015. Soil treatment using microbial biopolymers for anti-desertification purposes. Geoderma 253–254, 39–47. https://doi.org/10.1016/j.geoderma.2015.04.006.

Chávez-García, E., González-Méndez, B., 2021. Particulate matter and foliar retention: current knowledge and implications for urban greening. Air Qual. Atmos. Health 14, 1433–1454. https://doi.org/10.1007/s11869-021-01032-8.

Chen, Z., Feng, Q., Yue, R., Chen, Z., Moselhi, O., Soliman, A., Hammad, A., An, C., 2022. Construction, renovation, and demolition waste in landfill: a review of waste characteristics, environmental impacts, and mitigation measures. Environ. Sci. Pollut. Res. 29, 46509–46526. https://doi.org/10.1007/s11356-022-20479-5.

Climate and Environmental Change in the Mediterranean Basin - Current Situation and Risks for the Future. First Mediterranean Assessment Report MedECC. https://www.medecc.org/medecc-reports/climate-and-environmental-change-in-the-mediterranean-basin-current-situation-and-risks-for-the-future-1st-mediterranean-assessment-report/. n.d.

Cook-Patton, S.C., Drever, C.R., Griscom, B.W., Hamrick, K., Hardman, H., Kroeger, T., Pacheco, P., Raghav, S., Stevenson, M., Webb, C., et al., 2021. Protect, manage and then restore lands for climate mitigation. Nat. Clim. Chang. 11, 1027–1034. https://doi.org/10.1038/s41558-021-01198-0.

Croitoru, L., Sarraf, M., 2010. The Cost of Environmental Degradation : Case Studies from the Middle East and North Africa (World Bank). https://doi.org/10.1596/978-0-8213-8318-6.

Davies, C., Lafortezza, R., 2017. Corrigendum to "Urban green infrastructure in europe: Is greenspace planning and policy compliant?" [Land Use Policy 69 (December) (2017) 93–101]. Policy, Land Use. https://doi.org/10.1016/j.landusepol.2017.10.033.

Deeb, M., Grimaldi, M., Lerch, T.Z., Pando, A., Gigon, A., Blouin, M., 2016a. Interactions between organisms and parent materials of a constructed Technosol shape its hydrostructural properties. Soil 2, 163–174. https://doi.org/10.5194/soil-2-163-2016.

Deeb, M., Grimaldi, M., Lerch, T.Z., Pando, A., Podwojewski, P., Blouin, M., 2016b. Influence of organic matter content on hydro-structural properties of constructed Technosols. Pedosphere 26, 486–498. https://doi.org/10.1016/S1002-0160(15)60059-5.

Deeb, M., Grimaldi, M., Lerch, T.Z., Pando, A., Gigon, A., Blouin, M., 2016c. Interactions between organisms and parent materials of a constructed Technosol shape its hydrostructural properties. SOIL 2, 163–174. https://doi.org/10.5194/soil-2-163-2016.

Deeb, M., Desjardins, T., Podwojewski, P., Pando, A., Blouin, M., Lerch, T.Z., 2017. Interactive effects of compost, plants and earthworms on the aggregations of constructed Technosols. Geoderma 305, 305–313. https://doi.org/10.1016/j.geoderma.2017.06.014.

Deeb, M., Groffman, P.M., Blouin, M., Egendorf, S.P., Vergnes, A., Vasenev, V., Cao, D.L., Walsh, D., Morin, T., Séré, G., 2020. Using constructed soils for green infrastructure – challenges and limitations. SOIL 6, 413–434. https://doi.org/10.5194/soil-6-413-2020.

Deeb, M., Grimaldi, M., Aroui, H., Mthimkhulu, S., Van Antwerpen, R., Podwojewski, P., 2021. Long-term effect of sugarcane residue management and chemical fertilization on soil physical properties in South Africa. Soil Sci. Soc. Am. J. 85, 1913–1930. https://doi.org/10.1002/saj2.20326.

Droogers, P., Immerzeel, W.W., Terink, W., Hoogeveen, J., Bierkens, M.F.P., van Beek, L.P.H., Debele, B., 2012. Water resources trends in Middle East and North Africa towards 2050. Hydrol. Earth Syst. Sci. 16, 3101–3114. https://doi.org/10.5194/hess-16-3101-2012.

Erhart, E., Hartl, W., 2003. Mulching with compost improves growth of blue spruce in Christmas tree plantations. Eur. J. Soil Biol. 39, 149–156. https://doi.org/10.1016/S1164-5563(03)00030-X.

FAO, 2015. Status of the World's Soil Resources: Main Report (FAO).

Fehmi, J.S., Kong, T.M., 2012. Effects of soil type, rainfall, straw mulch, and fertilizer on semi-arid vegetation establishment, growth and diversity. Ecol. Eng. 44, 70–77. https://doi.org/10.1016/j.ecoleng.2012.04.014.

Gilby, B.L., Olds, A.D., Duncan, C.K., Ortodossi, N.L., Henderson, C.J., Schlacher, T.A., 2020. Identifying restoration hotspots that deliver multiple ecological benefits. Restor. Ecol. 28, 222–232. https://doi.org/10.1111/rec.13046.

Grantz, D.A., Vaughn, D.L., Farber, R., Kim, B., Zeldin, M., VanCuren, T., Campbell, R., 1998. Seeding native plants to Restore Desert farmland and mitigate fugitive dust and PM10. J. Environ. Qual. 27, 1209–1218. https://doi.org/10.2134/jeq1998.00472425002700050028x.

Haapala, T., Palonen, P., Korpela, A., Ahokas, J., 2014. Feasibility of paper mulches in crop production —a review. Agric. Food Sci. 23, 60–79. https://doi.org/10.23986/afsci.8542.

Hassani, A., Azapagic, A., Shokri, N., 2021. Global predictions of primary soil salinization under changing climate in the 21st century. Nat. Commun. 12, 6663. https://doi.org/10.1038/s41467-021-26907-3.

Hsu, H., Dirmeyer, P.A., 2023. Soil moisture-evaporation coupling shifts into new gears under increasing CO2. Nat. Commun. 14, 1162. https://doi.org/10.1038/s41467-023-36794-5.

Hu, J., Wu, J., Qu, X., Li, J., 2018. Effects of organic wastes on structural characterizations of humic acid in semiarid soil under plastic mulched drip irrigation. Chemosphere 200, 313–321. https://doi.org/10.1016/j.chemosphere.2018.02.128.

Hulvey, K.B., Leger, E.A., Porensky, L.M., Roche, L.M., Veblen, K.E., Fund, A., Shaw, J., Gornish, E.S., 2017. Restoration islands: a tool for efficiently restoring dryland ecosystems? Restor. Ecol. 25, S124–S134. https://doi.org/10.1111/rec.12614.

IPBES, 2018. Assessment Report on Land Degradation and Restoration | IPBES secretariat. https://www.ipbes.net/node/28328.

Iqbal, R., Raza, M.A.S., Valipour, M., Saleem, M.F., Zaheer, M.S., Ahmad, S., Toleikiene, M., Haider, I., Aslam, M.U., Nazar, M.A., 2020. Potential agricultural and environmental benefits of mulches—a review. Bull. Natl. Res. Cent. 44, 75. https://doi.org/10.1186/s42269-020-00290-3.

Issoufou, A.A., Soumana, I., Maman, G., Konate, S., Mahamane, A., 2020. Dynamic relationship of traditional soil restoration practices and climate change adaptation in semi-arid Niger. Heliyon 6, e03265. https://doi.org/10.1016/j.heliyon.2020.e03265.

Jang, J., 2020. A review of the application of biopolymers on geotechnical engineering and the strengthening mechanisms between typical biopolymers and soils. Adv. Mater. Sci. Eng. 2020, e1465709 https://doi.org/10.1155/2020/1465709.

Kader, M.A., Singha, A., Begum, M.A., Jewel, A., Khan, F.H., Khan, N.I., 2019. Mulching as water-saving technique in dryland agriculture: review article. Bull. Natl. Res. Cent. 43, 147. https://doi.org/10.1186/s42269-019-0186-7.

Keesing, F., Belden, L.K., Daszak, P., Dobson, A., Harvell, C.D., Holt, R.D., Hudson, P., Jolles, A., Jones, K.E., Mitchell, C.E., et al., 2010. Impacts of biodiversity on the emergence and transmission of infectious diseases. Nature 468, 647–652. https://doi.org/10.1038/nature09575.

Kirschner, G.K., Xiao, T.T., Blilou, I., 2021. Rooting in the desert: a developmental overview on desert plants. Genes 12, 709. https://doi.org/10.3390/genes12050709.

Leclercq-Dransart, J., Demuynck, S., Douay, F., Grumiaux, F., Pernin, C., Leprêtre, A., 2020. Comparison of the interest of four types of organic mulches to reclaim degraded areas: a field study based on their relative attractiveness for soil macrofauna. Ecol. Eng. 158, 106066 https://doi.org/10.1016/j.ecoleng.2020.106066.

Li, C., Pan, C., 2018. The relative importance of different grass components in controlling runoff and erosion on a hillslope under simulated rainfall. J. Hydrol. 558, 90–103. https://doi.org/10.1016/j.jhydrol.2018.01.007.

Li, C., Pan, C., 2020. Overland runoff erosion dynamics on steep slopes with forages under field simulated rainfall and inflow. Hydrol. Process. 34, 1794–1809. https://doi.org/10.1002/hyp.13692.

Li, C., Fu, B., Wang, S., Stringer, L.C., Wang, Y., Li, Z., Liu, Y., Zhou, W., 2021a. Drivers and impacts of changes in China's drylands. Nat. Rev. Earth Environ. 2, 858–873. https://doi.org/10.1038/s43017-021-00226-z.

Li, F.-M., Song, Q.-H., Jjemba, P.K., Shi, Y.-C., 2004. Dynamics of soil microbial biomass C and soil fertility in cropland mulched with plastic film in a semiarid agro-ecosystem. Soil Biol. Biochem. 36, 1893–1902. https://doi.org/10.1016/j.soilbio.2004.04.040.

Li, M., Wang, W., Wang, X., Yao, C., Wang, Y., Wang, Z., Zhou, W., Chen, E., Chen, W., 2023. Effect of straw mulching and deep burial mode on water and salt transport regularity in saline soils. Water 15, 3227. https://doi.org/10.3390/w15183227.

Li, X., Qu, C., Li, Y., Liang, Z., Tian, X., Shi, J., Ning, P., Wei, G., 2021b. Long-term effects of straw mulching coupled with N application on soil organic carbon sequestration and soil aggregation in a winter wheat monoculture system. Agron. J. 113, 2118–2131. https://doi.org/10.1002/agj2.20582.

Li, Y., Zhang, C., Chen, C., Chen, H., 2018. Calculation of capillary rise height of soils by SWCC model. Adv. Civ. Eng. 2018, e5190354 https://doi.org/10.1155/2018/5190354.

Liu, L., Gudmundsson, L., Hauser, M., Qin, D., Li, S., Seneviratne, S.I., 2020. Soil moisture dominates dryness stress on ecosystem production globally. Nat. Commun. 11, 4892.

López-Urrea, R., Sánchez, J.M., Montoro, A., Mañas, F., Intrigliolo, D.S., 2020. Effect of using pruning waste as an organic mulching on a drip-irrigated vineyard evapotranspiration under a semi-arid climate. Agric. For. Meteorol. 291, 108064 https://doi.org/10.1016/j.agrformet.2020.108064.

Loudyi, D., Kantoush, S.A., 2020. Flood risk management in the Middle East and North Africa (MENA) region. Urban Water J. 17, 379–380. https://doi.org/10.1080/1573062X.2020.1777754.

Lu, N., Likos, W.J., 2004. Rate of capillary rise in soil. J. Geotech. Geoenviron. Eng. 130, 646–650. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:6(646).

Marzen, M., Iserloh, T., 2021. Chapter 15 - Processes of raindrop splash and effects on soil erosion. In Precipitation, J. Rodrigo-Comino, ed. (Elsevier), pp. 351–371. https://doi.org/10.1016/B978-0-12-822699-5.00013-6.

Miyasaka, S.C., Hollyer, J.R., Kodani, L.S., 2001. Mulch and compost effects on yield and corm rots of taro. Field Crop Res. 71, 101–112. https://doi.org/10.1016/S0378-4290(01)00154-X.

Moreno, M., de-Bashan, L.E., Hernandez, J.-P., Lopez, B.R., Bashan, Y., 2017. Success of long-term restoration of degraded arid land using native trees planted 11 years earlier. Plant Soil 421, 83–92. https://doi.org/10.1007/s11104-017-3438-z.

Naasz, R., Michel, J.-C., Charpentier, S., 2008. Water repellency of organic growing media related to hysteretic water retention properties. Eur. J. Soil Sci. 59, 156–165. https://doi.org/10.1111/j.1365-2389.2007.00966.x.

Negacz, K., Malek, Ž., de Vos, A., Vellinga, P., 2022. Saline soils worldwide: identifying the most promising areas for saline agriculture. J. Arid Environ. 203, 104775 https://doi.org/10.1016/j.jaridenv.2022.104775.

Negm, A.M., and Shareef, N. (2020). Introduction to the "Waste Management in MENA Regions." In Waste Management in MENA Regions Springer Water., A. M. Negm and N. Shareef, eds. (Springer International Publishing), pp. 1–11. https://doi.org/10.1007/978-3-030-18350-9_1.

Ni, J., Wang, Z.-T., Geng, X., 2023. Vegetation growth promotion and overall strength improvement using biopolymers in vegetated soils. Can. Geotech. J. https://doi.org/10.1139/cgj-2022-0049.

INRAE Institutionnel. North Africa and the Middle East through to the year 2050: towards a greater dependence on agricultural imports. https://www.inrae.fr/en/news/north-africa-and-middle-east-through-year-2050-towards-greater-dependence-agricultural-imports n.d.

Ohte, N., Koba, K., Yoshikawa, K., Sugimoto, A., Matsuo, N., Kabeya, N., Wang, L., 2003. Water utilization of natural and planted trees in the semiarid desert of INNER MONGOLIA. CHINA. Ecol. Appl. 13, 337–351. https://doi.org/10.1890/1051-0761(2003)013[0337:WUONAP]2.0.CO;2.

Pacheco, F.A.L., Sanches Fernandes, L.F., Valle Junior, R.F., Valera, C.A., Pissarra, T.C.T., 2018. Land degradation: Multiple environmental consequences and routes to neutrality. Curr. Opin. Environ. Sci. Health 5, 79–86. https://doi.org/10.1016/j.coesh.2018.07.002.

Padilla, F.M., Pugnaire, F.I., 2006. The role of nurse plants in the restoration of degraded environments. Front. Ecol. Environ. 4, 196–202. https://doi.org/10.1890/1540-9295(2006)004[0196:TRONPI]2.0.CO;2.

Pauleit, S., Zölch, T., Hansen, R., Randrup, T.B., Konijnendijk van den Bosch, C., 2017. Nature-based solutions and climate change–four shades of green. Nat.-Based Solut. Clim. Change Adapt. Urban Areas Link. Sci. Policy Pract. 29–49.

Pauleit, S., Hansen, R., Rall, E.L., Rolf, W., 2020. Urban green infrastructure: strategic planning of urban green and blue for multiple benefits. In The Routledge Handbook of Urban Ecology (Routledge) 931–942.

Pauleit, S., Vasquéz, A., Maruthaveeran, S., Liu, L., Cilliers, S.S., 2021. Urban green infrastructure in the global south. In: Shackleton, C.M., Cilliers, S.S., Davoren, E., du Toit, M.J. (Eds.), Urban Ecology in the Global South Cities and Nature. Springer International Publishing, pp. 107–143. https://doi.org/10.1007/978-3-030-67650-6_5.

Pimentel, D., Kounang, N., 1998. Ecology of soil Erosion in ecosystems. Ecosystems 1, 416–426. https://doi.org/10.1007/s100219900035.

Prăvălie, R., 2021. Exploring the multiple land degradation pathways across the planet. Earth Sci. Rev. 220, 103689 https://doi.org/10.1016/j.earscirev.2021.103689.

Prosdocimi, M., Tarolli, P., Cerdà, A., 2016. Mulching practices for reducing soil water erosion: a review. Earth Sci. Rev. 161, 191–203. https://doi.org/10.1016/j.earscirev.2016.08.006.

Qadir, M., Bahri, A., Sato, T., Al-Karadsheh, E., 2010. Wastewater production, treatment, and irrigation in Middle East and North Africa. Irrig. Drain. Syst. 24, 37–51. https://doi.org/10.1007/s10795-009-9081-y.

Qi, Y., Ossowicki, A., Yang, X., Huerta Lwanga, E., Dini-Andreote, F., Geissen, V., Garbeva, P., 2020. Effects of plastic mulch film residues on wheat rhizosphere and soil properties. J. Hazard. Mater. 387, 121711 https://doi.org/10.1016/j.jhazmat.2019.121711.

Radeloff, V.C., Mladenoff, D.J., Boyce, M.S., 2000. A historical perspective and future outlook on landscape scale restoration in the Northwest Wisconsin pine barrens. Restor. Ecol. 8, 119–126. https://doi.org/10.1046/j.1526-100x.2000.80018.x.

Ragab, R., Prudhomme, C., 2002. SW—soil and water: climate change and water resources Management in Arid and Semi-arid Regions: prospective and challenges for the 21st century. Biosyst. Eng. 81, 3–34. https://doi.org/10.1006/bioe.2001.0013.

Rajhi, H., Bardi, A., Ajmi, L., Hazoug, M., des Tureaux, T.H., Haq, I., Bousnina, H., Abichou, M., Podwojewski, P., 2023. Effect of multi sourced compost on a rainfed olive tree grove in an arid land: management practices to adapt to global climate change. J. Arid Environ. 218, 105058.

Ramón Vallejo, V., Smanis, A., Chirino, E., Fuentes, D., Valdecantos, A., Vilagrosa, A., 2012. Perspectives in dryland restoration: approaches for climate change adaptation. New For. 43, 561–579.

Rengasamy, P., 2006. World salinization with emphasis on Australia. J. Exp. Bot. 57, 1017–1023. https://doi.org/10.1093/jxb/erj108.

Rockström, J., Falkenmark, M., 2015. Agriculture: increase water harvesting in Africa. Nature 519, 283–285. https://doi.org/10.1038/519283a.

Rodríguez-Espinosa, T., Navarro-Pedreño, J., Gómez-Lucas, I., Jordán-Vidal, M.M., Bech-Borras, J., Zorpas, A.A., 2021. Urban areas, human health and technosols for the green deal. Environ. Geochem. Health. https://doi.org/10.1007/s10653-021-00953-8.

Rodriguez-Franco, C., Page-Dumroese, D.S., 2021. Woody biochar potential for abandoned mine land restoration in the U.S.: a review. Biochar 3, 7–22. https://doi.org/10.1007/s42773-020-00074-y.

Rokia, S., Séré, G., Schwartz, C., Deeb, M., Fournier, F., Nehls, T., Damas, O., Vidal-Beaudet, L., 2014. Modelling agronomic properties of Technosols constructed with urban wastes. Waste Manag. https://doi.org/10.1016/j.wasman.2013.12.016.

Ruiz, F., Safanelli, J.L., Perlatti, F., Cherubin, M.R., Demattê, J.A.M., Cerri, C.E.P., Otero, X.L., Rumpel, C., Ferreira, T.O., 2023. Constructing soils for climate-smart mining. Commun. Earth Environ. 4, 1–6. https://doi.org/10.1038/s43247-023-00862-x.

Saccone, P., Delzon, S., Pagès, J.-P., Brun, J.-J., Michalet, R., 2009. The role of biotic interactions in altering tree seedling responses to an extreme climatic event. J. Veg. Sci. 20, 403–414. https://doi.org/10.1111/j.1654-1103.2009.01012.x.

Salem, E.M., Kenawey, K.M.M., Saudy, H.S., Mubarak, M., 2021. Soil mulching and deficit irrigation effect on sustainability of nutrients availability and uptake, and productivity of maize grown in calcareous soils. Commun. Soil Sci. Plant Anal. 52, 1745–1761. https://doi.org/10.1080/00103624.2021.1892733.

Salhi, A., El Hasnaoui, Y., Pérez Cutillas, P., Heggy, E., 2023. Soil erosion and hydroclimatic hazards in major African port cities: the case study of Tangier. Sci. Rep. 13, 13158. https://doi.org/10.1038/s41598-023-40135-3.

Séré, G., Schwartz, C., Ouvrard, S., Sauvage, C., Renat, J.-C., Morel, J.L., 2008. Soil construction: a step for ecological reclamation of derelict lands. J. Soils Sediments 8, 130–136. https://doi.org/10.1065/jss2008.03.277.

Shackelford, N., Paterno, G.B., Winkler, D.E., Erickson, T.E., Leger, E.A., Svejcar, L.N., Breed, M.F., Faist, A.M., Harrison, P.A., Curran, M.F., et al., 2021. Drivers of seedling establishment success in dryland restoration efforts. Nat. Ecol. Evol. 5, 1283–1290. https://doi.org/10.1038/s41559-021-01510-3.

Shah, S.T., Ullah, I., Basit, A., Sajid, M., Arif, M., Mohamad, H.I., 2022. Mulching is a mechanism to reduce environmental stresses in plants. In: Akhtar, K., Arif, M., Riaz, M., Wang, H. (Eds.), Mulching in Agroecosystems: Plants, Soil & Environment. Springer Nature, pp. 353–376. https://doi.org/10.1007/978-981-19-6410-7_20.

Smagin, A., Sadovnikova, N., Smagina, M., 2019. Synthetic gel structures in soils for sustainable potato farming. Sci. Rep. 9, 18588. https://doi.org/10.1038/s41598-019-55205-8.

Smagin, A.V., 2021. Thermodynamic concept of water retention and physical quality of the soil. Agronomy 11, 1686.

Smagin, A.V., Sadovnikova, N.B., 2016. The complex of technologies for sustainable agriculture and landscaping in arid regions. Экологический Вестник Северного Кавказа 12, 10–13.

Smagin, A.V., Sadovnikova, N.B., Vasenev, V.I., Smagina, M.V., 2018. Biodegradation of some organic materials in soils and soil constructions: experiments, modeling and prevention. Materials 11, 1889.

Smagin, A.V., Budnikov, V.I., Sadovnikova, N.B., Kirichenko, A.V., Belyaeva, E.A., Krivtsova, V.N., 2022. Gel-forming soil conditioners of combined action: laboratory tests for functionality and stability. Polymers 14, 4665. https://doi.org/10.3390/polym14214665.

Snoussi, G., Nasri, B., Hamdi, E., Fouché-Grobla, O., 2024. Reuse of Tunisian excavated material into composite soil for rainwater infiltration within urban green infrastructure. Geoderma Reg. 36, e00748 https://doi.org/10.1016/j.geodrs.2023.e00748.

Sohi, S.P., Krull, E., Lopez-Capel, E., Bol, R., 2010. Chapter 2 - a review of biochar and its use and Function in soil. In: Advances in Agronomy Advances in Agronomy. Academic Press, pp. 47–82. https://doi.org/10.1016/S0065-2113(10)05002-9.

Song, B., Almatrafi, E., Tan, X., Luo, S., Xiong, W., Zhou, C., Qin, M., Liu, Y., Cheng, M., Zeng, G., et al., 2022. Biochar-based agricultural soil management: An application-dependent strategy for contributing to carbon neutrality. Renew. Sust. Energ. Rev. 164, 112529 https://doi.org/10.1016/j.rser.2022.112529.

Special Report on Climate Change and Land — IPCC site https://www.ipcc.ch/srccl/. n. d.

Thomas, S.C., Gale, N., 2015. Biochar and forest restoration: a review and meta-analysis of tree growth responses. New For. 46, 931–946. https://doi.org/10.1007/s11056-015-9491-7.

Tian, D., Xiang, Y., Seabloom, E., Wang, J., Jia, X., Li, T., Li, Z., Yang, J., Guo, H., Niu, S., 2023. Soil carbon sequestration benefits of active versus natural restoration vary with initial carbon content and soil layer. Commun. Earth Environ. 4, 1–6. https://doi.org/10.1038/s43247-023-00737-1.

Union, P.O. of the E, 2015. Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities : final report of the Horizon 2020 expert group on 'Nature-based solutions and re-naturing cities' (full version). Publ. Off, EU. https://op.europa.eu/en/publication-detail/-/publication/fb117980-d5aa-46df-8edc-af367cddc202.

Van Rensburg, L.D., Botha, J.J., Anderson, J.J., Hensley, M., 2012. The nature and FUNCTION of the in-field rainwater harvesting system to improve agronomic sustainability. Irrig. Drain. 61, 34–40. https://doi.org/10.1002/ird.1678.

Voelkner, A., Diercks, C., Horn, R., 2017. Compared impact of compost and digestate on priming effect and hydrophobicity of soils depending on textural composition. SOIL Discuss. 1–20 https://doi.org/10.5194/soil-2016-62.

Volaire, F., Barkaoui, K., Norton, M., 2014. Designing resilient and sustainable grasslands for a drier future: adaptive strategies, functional traits and biotic interactions. Eur. J. Agron. 52, 81–89. https://doi.org/10.1016/j.eja.2013.10.002.

von Arx, G., Graf Pannatier, E., Thimonier, A., Rebetez, M., 2013. Microclimate in forests with varying leaf area index and soil moisture: potential implications for seedling establishment in a changing climate. J. Ecol. 101, 1201–1213. https://doi.org/10.1111/1365-2745.12121.

Wang, J., Liu, H., Wu, X., Li, C., Wang, X., 2017. Effects of different types of mulches and legumes for the restoration of urban abandoned land in semi-arid northern China. Ecol. Eng. 102, 55–63. https://doi.org/10.1016/j.ecoleng.2017.02.001.

Wu, L., Qin, F., Feng, J., Huang, J., 2020. Regional climate effects of plastic film mulch over the cropland of arid and semi-arid regions in Northwest China using a regional climate model. Theor. Appl. Climatol. 139, 335–349. https://doi.org/10.1007/s00704-019-02974-x.

Yang, J., Duan, Y., Wu, X., Tian, Y., Yang, L., Zhang, Y., Liu, Z., Awasthi, M.K., Li, H., 2022. Long-term grass mulching waste recycling and evaluation activation of dissolved organic carbon. Chemosphere 287, 132454. https://doi.org/10.1016/j.chemosphere.2021.132454.

Yasuor, H., Yermiyahu, U., Ben-Gal, A., 2020. Consequences of irrigation and fertigation of vegetable crops with variable quality water: Israel as a case study. Agric. Water Manag. 242, 106362 https://doi.org/10.1016/j.agwat.2020.106362.