# *Review Article*

# REGREENING THE DESERT: A STEP TOWARDS GLOBAL FOOD SECURITY

# ABSTRACT

The global population is expected to surpass 11 billion by the end of the century, significantly increasing the demand for staple food crops. By 2050, food demand is projected to rise by approximately 50% outpacing population growth. However, vast desert regions, covering nearly one-third of the Earth’s land surface, pose significant challenges to local food production due to extreme environmental conditions. As a result, many desert nations rely heavily on food imports to ensure food security. In response, scientific advancements have focused on transforming non-arable desert lands into cultivable areas through innovative technologies. Over the past few decades, significant progress has been made in arid-land development, demonstrating the potential of science and technology to convert barren landscapes into productive agricultural zones. This review explores the breakthroughs in both open-field and controlled- environment agriculture that have enabled food production under extreme desert conditions, highlighting the latest technological innovations and their implications for global food security.

# Keywords: Desert agriculture, food security, open-field agriculture, controlled-environment agriculture

# INTRODUCTION

The global population is projected to reach [8.5 billion](https://www.un.org/sustainabledevelopment/blog/2015/07/un-projects-world-population-to-reach-8-5-billion-by-2030-driven-by-growth-in-developing-countries/) by 2030, 9.7 billion by 2050 and surpass 11 billion by the end of the century (UN, 2022). Currently, [about 11%](http://www.fao.org/3/y4252e/y4252e06.htm) of the world’s land surface is classified as arable and are under permanent crop rotation (FAO, 2022). However, factors such as climate change, urbanization, and soil degradation are expected to reduce the availability of arable land. According to FAO (2022), the per capita availably of arable land is expected to reach 0.15 ha by 2050. But the demand for staple food crops is anticipated to rise slightly faster than the global population, with an approximate 50% increase globally by the year 2050. As more people move out of extreme poverty and gain access to more diverse diets, the demand for meat, dairy and eggs are expected to grow more than 60% and demand for fruits and vegetables will grow even more. Consequently, by 2050, there will be a need to boost food production by 70% (IFPRI, 2017). Therefore, seizing every opportunity to optimize food production will be critical in the forthcoming years.

Covering about one-third of global land surface, deserts encompass extreme environmental conditions. Among the 2.7 billion people residing in drylands, it is estimated that about 40 million live in deserts that typically receive under 100 mm of rainfall a year (ICARDA, 2021). Life in these regions face significant challenges due to severe abiotic stresses, including extreme temperature fluctuations, intense solar radiation and water scarcity (Alsharif *et al*., 2020). The main factors behind this high radiation levels are the proximity of these deserts to the equator and the low cloud coverage that allows high amounts of radiation to reach the Earth’s surface. In addition, low annual rainfall combined with elevated temperatures leading to increases evaporation, contributes to the rapid depletion of water reserves in desert areas. The soil in these regions becomes exceptionally arid due to several factors, including intense wind erosion, sedimentation, daily temperature fluctuations and, most importantly, water deficiency. In most desert regions, the soil is characterized as dry “Aridisols” exhibiting very low water holding capacity, nitrogen content and organic matter, slightly alkaline pH, elevated levels of salt ions, higher phosphate, calcium carbonate, and magnesium carbonate contents in certain or all soil parts (Alsharif *et al*., 2020). Thus, the harsh desert environment limits local food production, leading the desert countries to heavily rely on imported food commodities for ensuring food security.

During the recent years, the scientific community were in search of alternative technologies and approaches to transform millions of desert-like, non-arable lands into cultivable areas in order to improve domestic food production and ensure food security in these regions. Decades of research and technological advancements have shown that desert agriculture is no longer confined to isolated patches such as oases, marking significant progress in the field. Considerable progress has been achieved within the past few decades on various aspects of arid-land development, providing ample evidence to demonstrate that with the aid of science and technology it is possible to convert these desert areas into flourishing lands capable of sustaining satisfactory standards of living. Agriculture has successfully expanded into marginal and degraded desert lands in numerous locations that were previously considered unsuitable for food production.

To address the challenges of farming in arid regions, two distinct classes of solutions have emerged: open field and controlled environment solutions. The breakthrough technologies which enabled food production in this most barren soil, under the harshest conditions are detailed below.

# INNOVATIONS IN OPEN-FIELD DESERT AGRICULTURE

Open-field agriculture in desert environments presents significant challenges due to extreme temperatures, scarce water resources and poor soil fertility. However, recent advancements in agricultural technology and innovative farming practices have enabled the successful crop cultivation in these harsh conditions. By leveraging strategies such as soil enhancement techniques, efficient irrigation systems and water harvesting techniques, additives for improved water and nutrient retention, agrivoltaics systems, and sand stabilization techniques, desert regions are increasingly being transformed into productive farmlands. This section explores key innovations that have revolutionized open-field desert agriculture, paving the way for sustainable food production in arid landscapes.

**SOIL ENHANCEMENT**

# *Desert Soilization*

Soil is in a rheological state when wet and in a solid state when dry, and it can easily transform between these two states. These mechanical characteristics of soil endow it with the two eco- mechanical attributes of self-repair and self-regulation. These two attributes are essential for soil to sustain its continuous ecological cycle and function as an optimal environment for plant growth. “Desert soilization”, i.e., the turning of sand into “soil,” is a remarkable transformation based on this revelation of the eco- mechanical attributes of soil. Carboxy methyl cellulose (CMC) an environmentally friendly, non-toxic and cost-effective plant derived material used to convert sand into soil. When sand granules are mixed with sodium carboxymethyl cellulose, which acts as a binding agent, they acquire the same mechanical properties and eco-mechanical attributes as natural soil. A small quantity of sodium CMC (as little as 1-5%) added to water can produce a highly viscous paste. When mixed with sand, each granule becomes coated with a sticky layer of the solution, forming an omni-directional integrative (ODI) constraint between contacting granules, and eliminating discrete particles. As a result, the sand exhibits properties similar to natural soil (Yi *et al*., 2021).

Soilized sand have good aeration and a strong ability to retain water and nutrients. Additionally, it has been confirmed that the “soilized” sand demonstrates strong resistance against wind erosion. The resistance is due to the omni-directional integrative (ODI) constraint, which binds the sand mass together in both rheological state when wet and its solid state when dry. After soilization and planting, diverse range of microorganisms is reported to proliferate rapidly in the soilized sand. Additionally, the plants growing in soilized sand exhibit greater biomass, denser and longer roots compared to those in typical desert soil (Yi and Zhao, 2016).

For large-scale desert solilization, water is sprayed on the desert surface by an irrigating machine, while the constraining material (CMC) is spread on the desert surface by a mechanical spreader. A rotary cultivator thoroughly mixes the constraining material with the top layer of desert sand to ensure uniform integration. This process results in the soilization of a 15–25 cm thick layer of sand in the desert. The constraining material is generally applied at a weight ratio of less than 0.3% to sand. To enhance plant growth, compound or organic fertilizers may be added to the soilized sand during sowing and planting (Yi *et al.,* 2021).

In 2016, the research team carried out a verification experiment in Ulan Butt Desert on 1.67 hectares area by planting in soilized sand. The successful growth of over 70 plant species showed the effectiveness of the experiment and received widespread recognition. In 2017, the research team implemented a “technology + industry” approach and established a 650-hectare research & development base in Ulan Butt Desert. By 2018, desert soilization projects were conducted in Ulan Butt Desert in Inner Mongolia, Taklimakan Desert in Xinjiang and the desertified land in Zoige, Sichuan, covering a total area over 650 hectares. In 2019, desert soilization was further expanded in Ulan Butt Desert in Inner Mongolia and in Taklimakan Desert in Xinjiang. Additionally, successful experiments were conducted in Sahara Desert and the Middle East, desertified areas in Tibet and the beach sand of Xisha Islands and Xiamen, covering an area over 1300 hectares (Yi *et al.,* 2021).

# *Liquid Nanoclay* (LNC)

Soils with low clay content have difficulty to retain moisture, making the right amount of clay essential for plant growth. The practice of using clay to enhance soil quality is not new, as farmers have been doing it for thousands of years (Mustafa, 2009). However, incorporating thick, heavy clay into soil has been labour-intensive and disruptive to underground ecosystems. Years of trials have been dedicated to developing a clay formula for a way of making a clay recipe that can easily blend with sand, transforming it into fertile, life-supporting soil. Recently, scientists have started to experiment with nanosized clay particles. This technology involves separating naturally occurring clay into extremely fine particles (200-300 nm), and mixing them with water to create Liquid Nano-Clay (LNC), which is used to convert sandy desert soils into fertile land (Al Ramahi, 2019). The natural regeneration of dry land into arable land generally takes around 7-15 years. However, with the application of LNC, any poor-quality sandy soils can be transformed into productive agricultural land in just seven hours (Sparleanu, 2021).

Liquid Nano-Clay is a completely natural product free from chemical additives. It is obtained by dispersing clay nanoflakes in aqueous media, generating subsequent laminar and turbulent flow conditions. This clay-water dispersion is formed due to the cationic properties of nanoclay particles. Clay particles carry a negative charge due to their chemical composition, while sand grains have a positive charge. This natural polarity allows them to bond upon contact. As a result, a 200-300 nanometer layer of clay forms around each sand particle, creating a snowflake-like structure. Water molecules act as anionic particles, enveloping each clay flake. The changes in flow conditions create tiny air bubbles around the clay flakes, enhancing the stability of the dispersion. The expanded surface area enables water and nutrients to adhere to the sand, forming chemical bonds rather than being lost as runoff through the soil. The nanoclay particles also generates additional surface area that promotes fungal growth and enhances water retention within the upper soil layers near plant roots, improving crop nutrition and water availability (Lovell, 2020).

The LNC mixture is applied using traditional irrigation methods, allowing it to permeate the soil and reach the root zone at a depth of 40-60 cm. The depth of the LNC layer is controlled by adjusting the duration of the LNC irrigation, as it percolates through the soil and adheres to sand particles (Jeffs, 2017). The LNC layer acts like a sponge, retaining water and nutrients, significantly reducing water loss (upto 65%) by preventing deep percolation. Thus, LNC enables plant growth in previously inhospitable areas while requiring 50-60% less water. A layer of LNC prevents fertilizers from leaching through the soil, thereby protecting both the underlying soil and water table from contamination. Beyond enhancing water retention and nutrient availability, LNC treatment also safeguards the land from soil erosion by wind. The surface temperature can also be lowered by up to 15°C, creating a more favorable environment for plant growth (Desert Control, 2022). LNC application can boost crop yield by 400% compared to untreated plots with the same quantity of seeds and fertilizers (Sparleanu, 2021). The treatment cost $2 per square meter and requires a 15- 20% reapplication after 4-5 years if the land is tilled (Jeffs, 2017).

Currently, Desert Control, a Norwegian company, is the only developer of nanoclay soil amendments. The company has completed pilot projects in Egypt, China, and Pakistan, and maintains a small demonstration plot in Dubai, where it cultivates carrot, pepper, and cauliflower. According to the company, pilot studies have demonstrated a 50-65% reduction in water consumption compared to conventional irrigation methods, along with improved fertilizer efficiency and reduced runoff. However, the high cost of the technology (between $4,500 and $4,800 per hectare) remains a significant barrier to widespread adoption in the near future (Al Ramahi, 2019). Field tests conducted in Al Ain in Abu Dhabi documented 108% increase in size of individual cauliflowers and carrots compared to the control area. Similarly, trials in Egypt also recorded a fourfold increase in wheat yield.

# MATERIAL ADDITIVES FOR WATER/NUTRIENT RETENTION

***Super Absorbent Polymers* (SAP)**

Water management is one of the most important challenges, especially in arid regions with severe freshwater shortages. To enhance agricultural production and ensure food security, researchers are exploring sustainable techniques that reduce irrigation water consumption. One promising approach is the use of soil additives like Super Absorbent Polymers (SAP) (also known as hydrogel) to improve soil properties and water productivity. Arid regions struggle with uncertain and inadequate rainfall, limiting agricultural productivity. The application of SAPs in those areas helps to cope up with this problem and increase crop productivity (Al Ramahi, 2019).

The SAPs can absorb large quantities of water many folds of their weight and retain it for long period under drought conditions. As the soil dries, the polymer hydrogels passively release the absorbed water into their surroundings. SAPs adsorb and store water that is normally lost to evaporation or groundwater, reducing the volume and frequency of irrigation up to 50% and therefore it reduces water loss and increase irrigation intervals in arid regions (Dabhi *et al*., 2013). This allows for better water management and conservation without compromising crop yields (Al Ramahi, 2019).

Previous research shows that the application of low concentrations of SAP by 0.001% can improve soil properties. In addition to reducing water usage, SAPs enhance nutrient retention and minimize nutrient leaching. SAPs are reported to maintain soil moisture and some of the nutrients for up to five years after their application (Jahan and Mahallati, 2019). Therefore, hydrogel application may be a useful technique to improve water and fertilizer use efficiencies in arid regions (Abobatta, 2019). SAP application also increased the activity and proliferation of mycorrhizal fungi and other soil microorganisms which enhanced the possibility of cultivation in desert areas (Jahan and Mahallati, 2019).

# *Superhydrophobic Sand Mulch*

Irrigated agriculture plays a crucial role in global food production, especially in arid and semi-arid regions. However, these regions endure massive evaporative losses that are compensated by exploiting limited freshwater resources. The cumulative effects of decades of unsustainable freshwater extraction in arid regions are now threatening food–water security. To increase water-use efficiency, plastic mulches have been used to reduce evaporation from soil. However, their non-biodegradability and eventual land-filling renders them unsustainable. Recently, biodegradable Superhydrophobic Sand (SHS) mulch, a bioinspired enhancement of common sand with a nanoscale wax coating, has emerged as a promising alternative to plastic mulches (Odokonyero *et al.*, 2022).

The Superhydrophobic Sand mulch was developed by a patented technology by combining common sand, abundant in arid regions, and paraffin wax, a biodegradable and cost-effective hydrophobic material that is available at an industrial scale. A nanoscale wax coating (∼20 nm-thick on sand grains reduces water evaporation from moist soils. When laid on the topsoil with a sub-surface irrigation system, a 5–10 mm-thick SHS layer prevents capillary rise of water and insulates the wet soil from solar radiation and dry air, and act as a diffusion barrier for the water vapor (Gallo *et al.,* 2021). By reducing evaporation, more water is remains in the root zone, enhancing plant health in arid regions. Studies show that a 5–10 mm-thick SHS mulch layer decreases evaporation by 56–78% and increases soil moisture by 25–45%, improving crop growth and development (Gallo *et al*., 2022).

Multiyear field trials under arid land conditions in western Saudi Arabia with tomato, barley, and wheat under normal irrigation demonstrated that SHS mulch application enhanced yields by 17–73%. Under brackish water irrigation (5500 ppm NaCl), SHS mulching boosted tomato and barley yields by 53–208%. By suppressing evaporation, the enhanced soil moisture under SHS mulches likely played a key role in attenuating the effects of salt stress by transporting salts away from the root region via percolation/capillarity, as evidenced by the 39-60% lower sodium concentration in the topsoil. Unlike plastic mulches, SHS is environmentally benign as it is made from sand/sandy soil and biodegradable paraffin wax. SHS application did not affect the soil–root–rhizosphere microbial communities. The rhizospheric environments were dominated by an assemblage of diverse bacterial communities, such as *Gamma proteobacteria, Alpha proteobacteria*, and *Bacteroidetes,* followed by *Firmicutes, Gemmatimonadetes*, and *Actinobacteria*, which could be responsible for the degradation of paraffin wax on the SHS. This makes SHS technology beneficial for irrigated agriculture in arid regions with limited water resources. After about 9 months of SHS application, paraffin wax is degraded due to microbial activity and solar radiation and SHS gets incorporated in the soil, obviating land-filling; additionally, there are no detectable effects on soil microbial compositions (Gallo *et al*., 2022).

# ORGANIC AMENDMENTS FOR SOIL RESTORATION

Soils in arid regions are reported to have poor physical, chemical and biological properties. Mineral natural amendments like bentonite clay and organic manures such as compost, have been widely recommended in improving physical properties of sandy soils, such as enhancing the moisture retention and water conductivity, aggregate stability, as well as improving soil chemical properties such as cation exchange capacity and organic matter content (Al-Kinani and Jarallah, 2021).

Using water-holding agents is one of the most common and widely used methods to enhance soil water conservation to improve agricultural production in arid desert regions. Biochar application can improve soil adsorption capacity, soil porosity, organic matter content and soil aeration, while reducing soil bulk density. This subsequently changes the patterns of water permeation and salinity transportation in the soil profile. In addition to improving soil physical properties, biochar also enhances plant root nutrient uptake, leading to increased crop yields in arid agricultural lands in desert regions (Yang and Ali, 2019).

Maximizing the rhizospheric microbial functions is crucial for reclaiming arid and semi-arid lands for optimal productivity. The potential role of these organisms in land restoration for enhancing plant productivity needs to be exploited. In many crops, rhizosphere microbial communities have been investigated and the application of Plant Growth Promoting (PGP) microbes offers boundless possibilities for soil and plant health, and stress alleviation. PGP organisms confer drought resistance in arid and semi-arid soils (Ayangbenro and Babalola, 2020).

# SAND STABILIZATION TECHNIQUES

Wind erosion poses a significant challenge for ecologists to stabilize sand dunes and transforming them into stable productive ecosystems. Sand barriers are commonly used to direct windblown, drifting sand to accumulate in a desired place, helping to reduce dust emissions caused by the impact of moving sand grains on the soil. One of the most effective and common sand control measures is the use of straw checkerboards, which effectively limit the movement of sand particles and contribute to dune stabilization (Pan *et al*., 2020).

Polylactic acid fiber (PLA) sand barriers are an innovative and environmentally friendly solution for sand stabilization with wide application prospects. PLA fiber completely degrades into carbon dioxide and water without producing any pollution to the environment (Shen *et al.*, 2017).

# AGRIVOLTAIC SYSTEM (AVS)

Energy and food are the two essential requirements for the growing human population and demand for both are increasing rapidly. In view of the future requirement of energy and food production in arid and semi-arid regions, Agrivoltaic system (AVS) has been proposed as a mixed system integrating solar panels and crop at the same time on the same land area to optimize land use. The primary goal of AVS is to simultaneously produce electricity and grow plants on the same land.

In the Agrovoltaic system, photovoltaic (PV) panels are installed at an elevated height to allow crop cultivation beneath them. The space between PV arrays can also be used for growing suitable crops (Santra *et al*., 2018). Additionally, the area directly under the panels can also be utilized for cultivation, as partial shading can be beneficial by reducing water loss from evapotranspiration during summer and drought conditions (Amaducci *et al*., 2018). However, selecting shade tolerant crops is essential. Crops with low height (preferably shorter than 50 cm) and with a certain degree of shade tolerance and low water requirements are most suitable for AVS.

At Central Arid Zone Research Institute, Jodhpur, 105 kW capacity AVS has been established in an area of one acre. During the kharif season, crops such as moth bean, mungbean, and cluster bean were successfully cultivated in the interspaces. Apart from these rainfed crops, cumin, isabgol, and chickpea were grown under irrigated conditions during rabi season. In addition to arable crops, perennial medicinal plants like Aloe vera were also cultivated. Several vegetable crops such as cabbage, chilli, garlic and onion thrived in the shaded areas beneath the PV panels. There is also a provision for rainwater harvesting from the top surface of PV modules in the AVS model established at Jodhpur. The stored water can be utilized for cleaning the deposited dust from top surface of PV modules and also to provide supplemental irrigation to crops grown underneath (Santra *et al*., 2018).

At Jodhpur, effective solar irradiation to generate electricity is available for an average of 4 to 5 hours in a day. Therefore, 1 kW PV system can produce 4-5 kWh of electricity per day. Consequently, a 105 kW AVS has the potential to generate at least 420 kWh of electricity in a clear sunny day. The estimated annual revenue from selling PV-generated electricity is around Rs. 7,60,000. Additionally, the system enables the harvesting of 1.5 lakh liters of rainwater, which can be used for supplemental irrigation, providing approximately 37.5 mm of irrigation over one acre. Agricultural activities within the AVS contribute an average income of Rs. 31574/-. Overall, the total income from the system is estimated to be Rs 7.5 to 8.0 lakh/acre/year (Santra *et al*., 2018).

The AVS technology provides a significant advantage by enabling the simultaneous production of food and energy. This dual-purpose approach offers economic benefits to farmers by generating additional income (Malu *et al.,* 2017). AVS will inevitably leads to altered microclimatic conditions, notably a reduced solar radiation and resulting changes in water balance (Adeh *et al.,* 2018). Solar panels help conserve water by acting as a barrier to evaporation, leading to lower temperatures and optimized PV-based electricity generation (Weselek *et al*., 2019). The crop coverage in between PV arrays will also check the soil erosion and reduces dust accumulation on PV module. Studies have also indicated a considerable improvement in the biomass in the soil beneath the solar panels. The land equivalent ratio can be improved from 1.42 to 1.62 and land use efficiency may increase by 60-70%. Furthermore, AVS contributes to environmental sustainability by reducing greenhouse gas emissions, with an estimated 598 tons of CO2 saved per year per hectare (Mahto *et al.,* 2021).

# IRRIGATION TECHNIQUES

As agriculture depends upon irrigation and water supply, farming in arid regions where water is scarce is a challenge. Water efficiency has been important to the growth of desert agriculture. Surface drip irrigation (SDI), subsurface drip irrigation (SSDI), central pivot irrigation etc. are all the modern ways by which desert agriculture have expanded.

# *Micro-Irrigation Techniques*

In arid or semi-arid regions, where water scarcity is a major concern, the use of drip irrigation plays a crucial role in improving water resource management. It enables water supply directly to plant base in small, regular amounts thereby minimizing wastage (Ouédraogo *et al*., 2021).

During recent years, Subsurface drip irrigation (SDI), has gained popularity in arid regions due to its ability to significantly reduce water losses through runoff, evaporation, and deep percolation. Subsurface irrigation using buried diffusers allows to deliver water to plants at the root level, reducing the likelihood of water loss from evaporation. Subsurface systems are comprised of diffusing parts that are directly connected to a water distribution pipe, which regulates water flow to plants. These diffusers function using gravity and conventional water pressure, ensuring an even and efficient water supply to crops (Wang *et al*., 2018).

Center pivot irrigation is an effective irrigation system with significant potential in desert regions. This system irrigates crops in a circular pattern around a central pivot, ensuring uniform water distribution. The design of this system is such that the sprinklers located near the pivot tend to cover a smaller area compared to the nozzles located at the end of the pivot. Center pivot irrigation allows farmers to efficiently irrigate large farmlands while reducing both water usage and labour requirements (MohammadAli *et al.*, 2020). The system achieves approximately 80% water application efficiency, which is considerably higher than traditional irrigation methods (Waller and Yitayew, 2016).

# *Solar Powered Smart Irrigation System*

Solar power presents a sustainable solution to the current energy crisis while also being environmental-friendly. Photovoltaic (PV) generation is an efficient approach for harnessing solar energy, and solar-powered irrigation systems are increasingly gaining performance in water-scarce regions. It mainly consists of two modules: solar pumping module and automatic irrigation module. In solar pumping module, a solar panel of required specification is mounted near the pump set**.** The panel generates electricity, which is stored in a battery through a control circuit. A converter circuit then supplies power to a submersible water pump, which draws water from a well and stores it in an overhead tank before distribution to the field (Rejekiningrum and Apriyana, 2021). In automatic irrigation module the water outlet valve of the tank is electronically controlled by a soil moisture sensing circuit. The sensor is placed in the cultivated field detects soil moisture content and converts into voltage readings. This voltage is compared to a reference voltage, which can be adjusted by the farmer to suit different crop requirements. The difference between these voltages determines the amount of water needed. A control signal is sent to a stepper motor, which adjusts the valve opening based on the voltage difference, thereby regulating water flow according to soil moisture levels (Harishankar *et al*., 2014).

# WASTEWATER RECYCLING

Wastewater reuse in irrigation is also often practiced in arid and semi-arid countries. Many studies emphasize the benefits of using wastewater, particularly treated water for crop irrigation, as it enhances agricultural productivity. The advantages of wastewater reuse include a reliable year-round water supply, high nutrient content that can reduce the need of chemical fertilizers, improved productivity on less fertile soils, and reduced environmental damage to freshwater ecosystems associated with eutrophication and algal blooms, etc. (Ungureanu *et al*., 2020).

# WATER DESALINATION TECHNOLOGIES

The agriculture sector accounts for about 70% of global water consumption, followed by energy supply, industry, and domestic sectors. Approximately 96.54% of Earth’s water is saline, with only 2.53% being freshwater (Mart´ınez-Alvarez *et al*., 2018). Desalinated water represents a reliable water source that overcomes climatological and hydrological constraints (Thimmaraju *et al*., 2018). After decades of protracted growth, desalination as a practice has witnessed a considerable rise over the recent years as arid countries seek to augment freshwater supplies. By 2019, approximately 21,123 desalination plants were installed in 150 countries. (Aende *et al.*, 2020). Saudi Arabia currently has the largest global desalination capacity by supplying 60% of its total water demand through desalination process (Darre and Toor, 2018).

Desalination is defined as any process which removes excess salts and minerals from water (or) the chemical process of changing seawater into potable water. The two primary desalination technologies used globally are thermal evaporation and membrane separation. In the thermal evaporation process, seawater is heated to its boiling point to generate water vapor which is then condensed to freshwater. Major thermal desalination processes are multistage-flash distillation (MSF) and multi effect distillation (MED or ME). In MSF, seawater is boiled at low pressure, causing steam to flash off, which is condensed and collected while in MED low- pressure steam induces seawater evaporation and the resulting vapor is condensed. MED technology is considered more cost effective and efficient than MSF (Thimmaraju *et al*., 2018). However, both MSF and MED require high energy input and are expensive. Over the past decade, seawater desalination using semi-permeable sea water reverse osmosis (SWRO) membranes has gained widespread adoption and currently dominates the desalination markets. The membrane-based treatment process is more efficient, occupies less physical space and consumes less energy compared to thermal evaporation process (Gorjian *et al*., 2022).

# *Seawater Reverse Osmosis (SWRO) desalination technique*

Reverse osmosis operates on a straightforward principle. When a semi-permeable membrane separates low-chloride and high-chloride water, water will naturally move from the low- chloride side to the high-chloride side. This process is called osmosis. The transfer of water in one direction generates a net pressure on the high-chloride side, which is called the osmotic pressure. By applying external pressure to the high-chloride side that exceeds the osmotic pressure, water is forced to move in the opposite direction, i.e., from the high-chloride to the low-chloride side. This process is called reverse osmosis. The resulting water is relatively pure compared to the original brine. SWRO plants do not require heat energy, but depend on substantial electricity to drive all the high- and low- pressure pumps. Energy costs are a major factor in the development of these plants. Additionally, membrane maintenance is expensive, adding to the overall costs of these desalination systems (Ullah and Rasu, 2019).

The costs of desalinated water per cubic meter are as high as $1.50 and even $4 in some cases (UNDP, 2013). In order to lower the expenses, some recent desalination plants have integrated large solar arrays in desert regions or established wind farms to operate using renewable energy resources.

# *Fertilizer Drawn Forward Osmosis (FDFO) desalination technique*

Energy-efficient desalination techniques offer a promising solution for supplying irrigation water in arid regions. Among these, Fertilizer Drawn Forward Osmosis (FDFO) is a remarkably low energy membrane desalination process specifically designed for irrigation. In this process, a fertilizer solution with high osmotic pressure serves as the draw solution (DS) to extract water from a saline feed source through a semipermeable membrane by utilizing the osmotic pressure gradient between the feed and draw streams (Phuntsho, 2012). Unlike conventional forward osmosis (FO) desalination, FDFO eliminates the need for draw solute separation and recovery, as the fertilizer itself enhances the quality of the produced water. Once the water is extracted, the dilutes fertilizer solution can be directly used for fertigation, provided it meets irrigation water quality standards in terms of salinity and nutrient composition (Phuntsho *et al*., 2011).

# *Humidification-dehumidification (HDH) desalination technology (Seawater greenhouses)*

A seawater greenhouse is a specialized greenhouse structure that enables the crop growth and the fresh water production in arid regions. It operates using only seawater and solar energy for desalination. Seawater is pumped into pipes in the greenhouse and trickled down over a spongy honeycomb-like evaporator. As air is drawn through this honeycomb surface, it cools and becomes more humid, creating favorable growing conditions for the greenhouse crops. At the back of the greenhouse, the cool air is drawn through a second evaporator containing seawater that has been heated by the sun in the ceiling pipes. The air then becomes hot and humid to the saturation point. When the hot humid air meets an array of vertical cold seawater pipes, fresh water condenses. The collected fresh pure water is then piped to a storage container and used for irrigation (Al-Ismaili and Jayasuriya, 2016).

The left-over brine serves as an effective coolant, absorbing heat as additional water evaporates from it, further cooling the air. The condensed desalinated water can be used for irrigating the crops. Unlike the traditional desalination methods, which are expensive and release large amounts of salty brine back into the sea, disrupting fragile ecosystems, the seawater greenhouse model is an eco-friendly alternative. Left over brine that not used in the cooling cycle is evaporated to produce salt. Seawater greenhouses offer the possibility of stable, climate-resistant agricultural production in regions where extreme weather makes farming challenging. Another untapped benefit of seawater greenhouses is the ability to “mine” elements like cobalt, lithium and magnesium from the brine.

# *Solar-powered desalination technologies*

The transition to renewable energy sources for desalination seems a very practical solution to mitigate the reliance on fossil fuels. In this context, solar-powered desalination appears as reliable technology with the potential to address freshwater shortages (Naderipour *et al*., 2021). Solar-powered desalination unit, transforms salt water into fresh water by converting the solar energy into heat, either directly or indirectly, to drive the desalination process. However, direct solar desalination produces limited output, making it unsuitable for commercial operation. Therefore, indirect solar desalination methods are commonly utilized to increase freshwater production. Indirect solar desalination combines two different technologies: solar energy collection (through the use of [photovoltaic panels](https://www.britannica.com/technology/photovoltaic-device)) is coupled with a proven desalination method such as [multistage flash (MSF) distillation](https://www.britannica.com/science/multistage-flash-distillation), multiple effect evaporation (MEE), or [reverse osmosis](https://www.britannica.com/science/reverse-osmosis) (RO) (Eterafi *et al*., 2021). Employing renewable solar energy as a supplementary heat source can help to eliminate fossil fuel energy consumption, significantly reducing operating costs and improving the feasibility of commercial desalination plants.

# ATMOSPHERIC WATER HARVESTING

Various water desalination technologies, have been developed to utilize seawater or wastewater. However, these methods rely on natural water sources, making them primarily feasible in coastal areas and are generally inaccessible for landlocked regions. As an alternative, atmospheric water, which is available regardless of geographical or hydrologic conditions, is emerging as a sustainable water resource.

The Earth’s atmosphere holds water in the form of water droplets or vapor, accounting for approximately 10% of global freshwater sources and providing an estimated 50,000 km3 of water. Atmospheric water harvesting (AWH) has emerged as a promising solution to address the water scarcity, particularly in arid and inland areas lacking liquid water sources. There are two main approaches to collect water from the atmosphere: the first is fog collection, whereas the second is through condensation of vapor on surfaces with a temperature below the dew point. Fog collection is the harvesting of water from fog using large pieces of vertical mesh netting to induce the fog-droplets to flow down towards a trough below. The setup is commonly known as a fog fence, fog collector or fog net. Through condensation, atmospheric water vapor from the air condenses on cold surfaces into droplets of liquid water known as dew. Water condenses onto the array of parallel wires and collects at the bottom of the net. This method requires no external energy and relies solely on temperature fluctuation, making it viable option for deployment in less developed areas (Kaseke and Wang, 2018).

Recent advancement is atmospheric water absorption is by using absorbents, which extract water vapor from air and release it as vapor upon heating into an enclosed space. The vapor then condenses on a cold surface, producing fresh water. As an absorbent, a notable innovation is the development of metal-organic frameworks (MOFs), a class of highly hygroscopic materials capable of capturing water even at low relative humidity levels (as low as 25%). MOFs have shown significant potential for water harvesting in arid regions, offering an efficient and scalable solution to water scarcity (Meng *et al*., 2022).

# INNOVATIONS IN CONTROLLED ENVIRONMENT DESERT AGRICULTURE

Controlled environment agriculture (CEA) is the modification of the natural environment to achieve optimum plant growth. Modifications can be applied to both the aerial and root environments to enhance crop yields, extend the growing season and enable cultivation during off-season periods. Various environmental factors including air and root temperatures, water, light, carbon dioxide levels, humidity, and plant nutrition can be regulated to maximize the plant growth and economic returns.

# DESERT GREENHOUSES

Arid regions are characterized by extreme climatic conditions such as prolonged hot summer season with midday temperature exceeding 45°C, intense solar radiation flux reaching up to 30 MJ m-2 per day, and dry, dusty weather with relative humidity dropping below 10% at noon. However, coastal arid areas may experience high humidity during the hottest months and water resources remain scarce and often brackish. These challenging conditions make horticultural crop cultivation difficult, leading many countries to rely heavily on food imports. It is therefore important to consider how to create cool environments for cultivation in hot climates (Abdel-Ghany *et al*., 2012).

Although greenhouses are generally regarded as necessary only to provide a warm environment in cold climates, properly designed greenhouse structure with effective cooling systems can significantly improve growing conditions in hot environments. Protected cultivation within greenhouses presents a viable solution for enhancing agricultural productivity in arid regions, offering a controlled environment that mitigates extreme heat and optimizes plant growth.

Desert Greenhouses must ensure good light transmission for optimal plant growth. Covering materials with excellent PAR transmission is recommended (Glass, PE, PVC, polycarbonate, ETFE-film, etc.). In arid and semi-arid regions, regular cleaning of accumulated dust on greenhouse roof is essential, as dust buildup can rapidly reduce light transmission. Sprinklers are an option, but now different cleaning machines are available in the markets. Desert greenhouses should have a maximum ventilator area between 15- 30% of the total covered area. Large-volume greenhouses are recommended for arid environments, achieved by increasing the width and height of the spans. A higher volume allows greater light transmission and helps to maintain lower temperatures in the lower 3 m crop area, while temperatures near the roof may reach 45-60°C. Additionally, the construction should be wind proof and well insulated, with an efficient combination of cooling systems to maintain suitable growing conditions in extreme desert climates (Baeza and Kacira, 2017).

Natural ventilation combined with horizontal positioned foggers creates uniform cooling effects (Tamimi *et al*., 2013). Some growers also utilize evaporative cooling by employing cheap low-pressure mist to improve the cooling under greenhouses. One of the most widely used cooling methods in arid and semi-arid regions is the wet pad and fan system, which can lower temperature by 10-12°C while increase humidity in the greenhouse with pure fresh water available.

Maximum ventilation capacity can be achieved using screenhouses as growing structures. In desert regions where radiation levels are extremely high, the screen used must provide significant shading effect. However, dust accumulation can further increase shading, significantly reducing air-exchange and limiting the effectiveness of screenhouses unless regular cleaning is performed throughout the growing cycle. Some greenhouse models in the market feature roof exchangeable cover (i.e. plastic film and shading screen), which enables the selection of most suitable cover material based on crop requirements at different times of the day or throughout the growing cycle (Baeza and Kacira, 2017).

In most arid regions, low density polyethylene (LDPE) film is the most popular material due to its affordability and simplicity. Selective shading is crucial in arid conditions and can be achieved using either a permanent covering material with a near infrared (NIR) filter or a movable screen with NIR reflection. Therefore, NIR-reflecting plastic films are recommended for covering greenhouse permanently in these regions (Abdel-Ghany *et al*., 2012). Alhamdan and Al-Helal (2009) reported that the high radiation, extreme temperature and dusty winds in arid areas significantly reduce the lifespan of polyethylene (PE) films used as greenhouse covers. In relation to mechanical stress, the best is to use multilayer film (i.e. three layers, PE + EVA+ PE) instead of monolayer or to use more rigid materials as polycarbonate or glass.

# VERTICAL FARMING

The vertical farming is an advanced indoor agricultural model on a high-rise multi-level factory design. Key features include innovative use of recycled water augmented by rainwater or desalinated water, automatic air-temperature and humidity control, solar panel lighting and heating, and tunable 24-hour LED illumination. The LED equipment can be programmed to emit a specific light spectrum tailored to the photosynthetic needs of different crops throughout their growth cycle. When coupled with precise temperature and humidity regulation, this controlled environment minimizes or even eliminates the impact of seasonal variations, allowing for consistent and efficient crop production year-round.

A recent development in vertical farming that brings hope for future particularly in desert regions is Pink LED technology. A Netherlands-based company called PlantLab has devised a method for growing plants indoors using an unearthly pink-purple light made by the combination of red and blue LED lights instead of sunlight. While plants rely on sunlight for photosynthesis, they only require specific parts of the light spectrum. By providing only the necessary wavelengths, red and blue LEDs enhance photosynthetic efficiency, resulting in stronger and healthier plants. The usefulness of this technology is that its efficient water management in which water used within the indoor environment is recycled for reuse. As a result, water is efficiently economized. Furthermore, since plants are grown indoors, they are protected from pests, eliminating the need for pesticides and lowering the production costs. With climate-controlled indoor farms requiring less energy, water, and space than traditional agriculture, Pink LED technology presents a sustainable and resource efficient solution for food production in arid and desert regions (Mbaga, 2014).

# SOILLESS CULTIVATION TECHNIQUES

In combination with desert greenhouses, soilless cultivation is gaining popularity. Different soilless cultivation techniques include hydroponics, aeroponics and aquaponics. Although it requires high initial capital, it offers significant advantages such as high productivity, efficient water and land use, and protects the environment. This type of protected agriculture shields crops from outside unfavorable weather or soil conditions and excessive water evaporation, creating a closed space to cultivate and finds scope in desert agriculture (Fussy and Papenbrock, 2022).

# *Hydroponic Cultivation*

Hydroponics is a cultivation technique involves growing plants in a soil-free culture with nutrient solutions. The plants are suspended in an inert growing medium, such as rock wool or perlite, and provided with nutrients, or the roots are directly immersed in a continuously flowing nutrient solution, as seen in the nutrient-film technique (Lakkireddy *et al*., 2012). Air conditioning ensures a steady airflow which can be enriched with carbon dioxide (CO2) to enhance plant growth and development. Both ambient and nutrient temperatures can be precisely regulated to optimize the plant growth. Any excess nutrients and water not absorbed by the roots can be recycled rather than lost to the system (Benke and Tomkins, 2018).

Hydroponics allows year-round production of large quantities of high-quality fruits and vegetables particularly in arid regions. In combination with greenhouses and advanced technology, hydroponics systems can achieve high productivity while conserving water and land. Despite requiring significant capital investment, hydroponics offers an environmentally sustainable solution for food production in water-scarce environments (Mbaga, 2014).

# *Aeroponic Cultivation*

Aeroponic cultivation is a variant of hydroponics, in which plant roots are suspended in the air and periodically misted with nutrient solution. This technique ensures optimal conditions for plant growth, including precise control over nutrient levels, temperature, aeration and pH. Oxygen is infused into the nutrient mist, allowing plant roots to absorb nutrients more efficiently which accelerates growth while preventing algae formation and enhancing overall yield. Plant roots are suspended mid-air inside a chamber kept at a 100% humidity level and fed with a fine spray of nutrient solution. This mid-air feeding allows the roots to absorb much needed oxygen, thereby significantly boosts metabolism, leading to growth rates up to 10 times faster than cultivation in soil. And there is nearly no water loss due to evaporation (Lakkireddy *et al*., 2012). Due to its efficient resource utilization and high productivity, aeroponics presents a sustainable and innovative solution for modern agriculture, particularly in water-scarce environments.

# *Aquaponic Cultivation*

Aquaponics is an innovative agricultural system that integrates aquaculture with hydroponics, creating a closed-loop system for the simultaneous production of ﬁsh and plants. Aquaponics combines two primarily productive systems: recirculating aquaculture system (RAS) and hydroponic cultivation. Recirculating aquaculture involves the farming of ﬁsh and crustaceans in a controlled water tank, while hydroponic cultivation enables plant growth in a nutrient rich water medium without soil (Conijn *et al*., 2018). Aquaponics emerges as a promising technology for sustainable food production in arid regions, where conventional farming is limited by water scarcity and poor soil quality. By efficiently recycling water and nutrients within the system, aquaponics minimizes resource waste while maximizing agricultural output. As climate change continues to impact global food security, this integrated approach offers a resilient and sustainable method to enhance food production for challenging environments.

# CONCLUSION

Desert agriculture is more important than ever before as global population rises. Countries and regions that are not water-secure are no exception to increasing population and thus increasing demand for food. Growing more food from deserts which are otherwise unproductive and resource-strapped areas has become the need of the hour. Many innovative solutions have emerged in both open field and controlled environments. While these solutions seems promising, many of the technologies are at infant stage and needs further validations. Some technologies still suffers from challenges that prevent them from achieving broad scale adoption. Holistic evaluation of pros and cons of each technology before implementation becomes highly critical to design a viable and sustainable solution for regreening the deserts.

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