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MASDAR TECHNOLOGY JOURNAL

Sustainable Agriculture for Arid Climates

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FOREWORD

With the world's population expected to exceed 9 billion by 2050, efficient and sustainable production and distribution of food are becoming increasingly important. This is particularly true for countries with arid climates and harsh environmental conditions, such as the United Arab Emirates.

Today, the global food value chain is responsible for 20 per cent to 30 per cent of greenhouse gas emissions, roughly 30 per cent of all energy consumption and 70 per cent of annual freshwater withdrawals. These figures will only rise in the future.

It is therefore imperative to act now. At Masdar, the Abu Dhabi Future Energy Company, we believe that solutions lie in close collaborations between producers, technology providers, policymakers, investors, the general public and other stakeholder groups. The first step in this direction is creating awareness through events such as Abu Dhabi Sustainability Week, one of the world's largest sustainability gatherings that is hosted by Masdar every year in January.

In addition, through Masdar City, Abu Dhabi's flagship sustainable development, we aim to demonstrate that sustainability is not only viable, but can enhance quality of life by deploying and showcasing cutting-edge food production technologies and systems, such as collaborating with Madar Farms to focus on delivering the future of sustainable agriculture to the UAE.

As this report details, a number of technologies and techniques are currently being used to enhance sustainable agriculture, both in low-tech open-farming as well as high-tech settings. Some are based on broad technological advances, such as the Internet of Things, cloud computing and nanotechnology, whereas others are agriculture-specific and focus on the likes of hydroponics and various soil enhancements.

I hope you find the report informative and join us in our drive for sustainability as part of our #WeAreCommitted campaign, which has been launched on the back of Abu Dhabi Sustainability Week 2019.

Mohamed Jameel Al Ramahi

Chief Executive Officer of Masdar

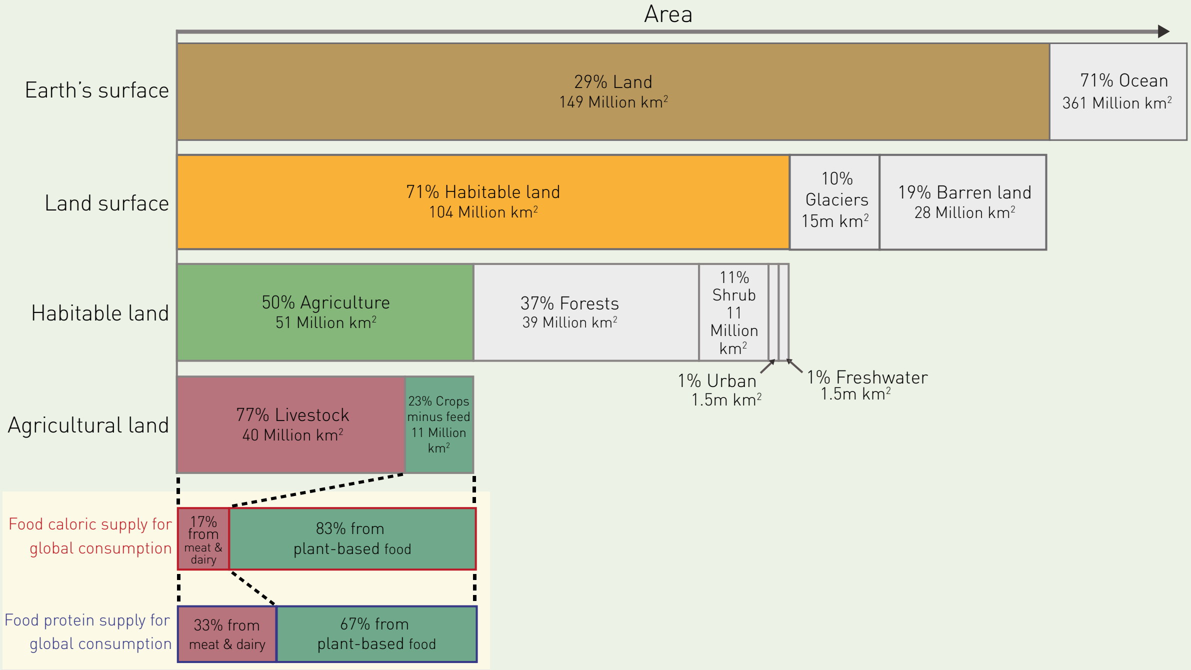
Sustainable Agriculture for Arid Climates

INTRODUCTION

Agriculture is a critical element of every human-inhabited region of the world. With a global population of 7.6 billion, growing to a projected 9 billion by 2050, demand for food will only rise. Today, traditional agriculture is limited to the ~2.5 billion hectares of arable land (with ongoing access to freshwater and fertile soil), of which ~1.5 billion hectares are actually used for crop cultivation. However, a large and growing portion of the world's inhabited land is arid, limiting the viability of traditional agricultural techniques for growing food. Additionally, climate change is further stressing these regions on resources, and degrading soil, water, and overall environmental conditions at an alarming rate of 23 hectares *per minute*. As a result, many arid regions, like the UAE, either heavily rely on imported food with high carbon footprints, or if economically disadvantaged, give rise to severely underfed and malnourished populations.

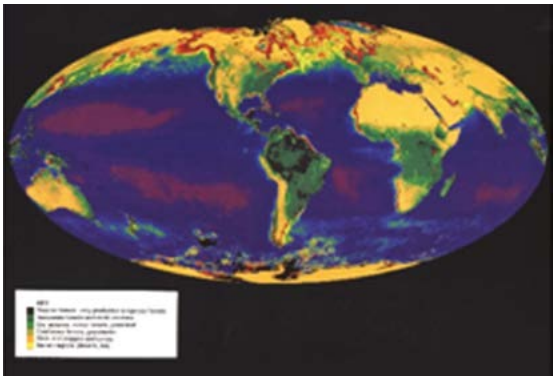
Figure title: Global surface area allocation for food production

The breakdown of Earth surface area by functional and allocated uses, down to agricultural land allocation for livestock and food crop production, measured in millions of square kilometers. Area for livestock farming includes grazing land for animals and arable land used for animal feed production. The relative production of food calories and protein for final consumption from livestock versus plant-based commodities is also shown.



Data source: based on the UN Food and Agricultural Organisation (FAO) Statistics.
The data visualization is available at OurWorldinData.org. There you find research and more visualizations this topic.

Arid regions are characterized by a severe lack of water, caused by a combination of minimal rainfall and high evapotranspiration (due to solar irradiation, humidity, and wind), and cover nearly a third of global landmass. Additionally, nearby fertile land is at high risk for overuse and nutrient depletion. In combination with aridity, nations with high purchasing power like the UAE often resort to importing food, but this comes with high costs, and an outsized carbon footprint. Poorer regions do not even have this option, and often rely on a combination of unreliable, temporary water solutions and water tankers, while many residents are deprived of adequate nutrition. Finally, proximity to urban areas also dictates the type and degrees of challenges in producing food. Access to urban regions implies access to infrastructure, like water, electricity, transportation, whereas remote regions require unique solutions to these challenges.



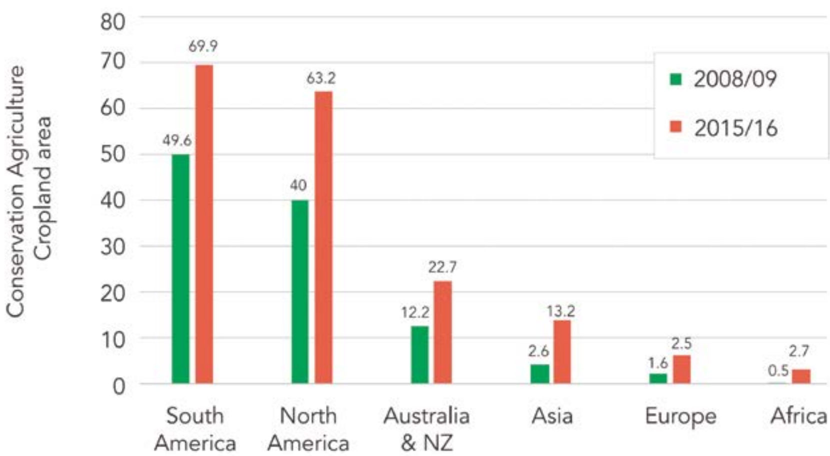
Source: This image comprises data from the Advanced Very High Resolution Radiometer aboard the National Oceanic and Atmospheric Administration's Polar Orbiting Environmental Satellite series to map global vegetation cover

Plants need water, sunlight, and nutrients to grow. Most plants absorb water and nutrients through soil and use water to transport moisture and nutrients back and forth through the plant's roots and leaves. As a result, most farming solutions modify physical and chemical aspects of the environment (including light, soil composition, water availability, and ambient temperature) to optimise for plant growth and metabolic productivity. In arid regions, crop cultivation is challenging because of tough environmental conditions, and characteristically low and/or unsteady supplies of fresh water.

To meet the requirements of farming in arid regions, two distinct classes of solutions have emerged: open field and controlled environment solutions. Open field solutions have the most immediate applicability in arid regions, particularly those of limited economic means. Additionally, 98% of the world's produce is grown in open fields, making this a well-studied practice, with many variations on solutions to limitations on soil, air, water, and sunlight. These solutions include "smart" irrigation, soil enhancement/conservation, breeding and genetic modification, low- or zero-energy crop storage, digital solutions and novel business models. Often, low-tech solutions and conservational principles applied to traditional farming are sufficient to extend the usable lifetime and yield of an arable soil. Several natural "conservation agriculture" techniques have already gained significant momentum[1] in the past decade, with an estimated 175 million hectares (~7% of all arable land) under use (see figure below).

[1]https://journals.openedition.org/factsreports/3966

Figure title: Cropland area taken up by conservation agriculture 2008/2009 to 2015/2016, Million Ha

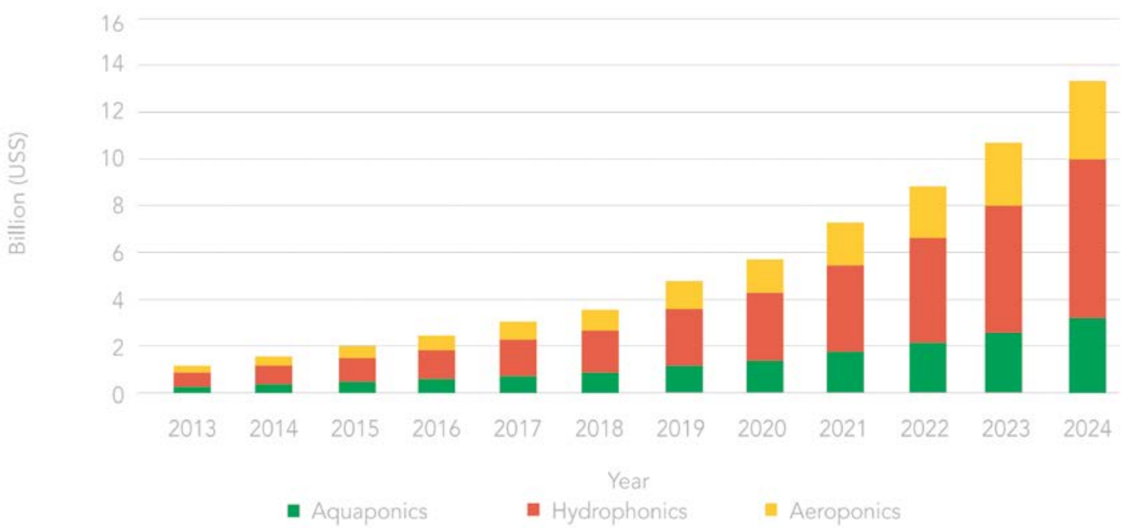


Source: http://www.blwk.co.za/

Conversely, controlled environments rely on creating synthetic boundaries around an "indoor" productive unit, and often rely on artificial conditions (light, soil, energy, water) to produce plants where food would not otherwise grow. These solutions include plastic greenhouses, high-tech greenhouses, and vertical farms, including aquaponics, hydroponics, and aeroponic solutions, among others. Solutions like greenhouses have been in commercial use for decades, whereas decentralized solutions, like vertical farms, have recently been introduced – especially in developed urban regions; the U.S. alone comprises a $3.8 billion market in 2018 (see figure below). Controlled environment farming offers technological advances and may eventually be a prominent solution. Meanwhile, open field agriculture in arid regions, which is often executed by less-skilled workers with a low penetration of technology, will persist for the near- and mid-term and tends to be the only viable solution in regions with low purchasing power, despite the staggering inefficiencies.

The innovative solutions that have emerged in both open field and controlled environments, while promising, still suffer from challenges that prevent them from achieving broad scale adoption. Generally, when optimizing for one or more requirements, solutions become unsustainable because of cost, environmentally unsafe practices, over-reliance on human labour or critical natural resources, or sacrifices on nutritional quality of produce. Balancing the holistic pros and cons of target solutions becomes highly critical to design for both viability and sustainability, particularly as accelerated population growth demands more prolific food production from these otherwise unproductive and resource-strapped areas.

Figure title: US vertical farming market size by technology 2013-2024



Source: http://www.blwk.co.za/

Masdar City: Abu Dhabi's flagship sustainable development

A benchmark for sustainable urban development globally, Abu Dhabi's Masdar City is also a hub for cleantech innovation and entrepreneurship. Building on numerous past initiatives (notably in the clean and smart mobility space), and with food security now placed at the top of the UAE strategic agenda, Masdar City has initiated several pilots in the sustainable agriculture landscape, with its strategic partners, such as the UAE Minister of State for Food Security. Food production and distribution is one of the top drivers of carbon emissions and strain on natural resources, and making the entire value chain more sustainable is an urgent necessity.

The objective of these pilots is to raise awareness of progress in sustainable agriculture and demonstrate emerging urban farming solutions and technologies which will be an integral part of the future of cities and food systems, in the UAE and globally.

A first initiative is a vertical farming pilot facility based in Masdar City. Developed in collaboration with UAE-based agtech start-up Madar Farms, the pilot will consist of 4 container-based vertical farms growing a diverse range of crops, from leafy greens, to microgreens and strawberries. The initiative will also include, based on market research and performance data collected from the pilot farms, the development of a white paper exploring the techno-commercial viability of vertical farming and identifying key pre-requisites for its development in the UAE.

Another initiative will consist of a home-farming exhibition based in Masdar City's Eco Villa. Also developed with Madar Farms, the exhibition, which will be open to the public throughout 2019, will showcase several emerging smart solutions, around food, water and waste recycling and production, at the home level.

Finally, Masdar City is supporting UAE-based start-up De L'Arta, in the development of its pilot composting facility, located in Masdar City and which aims at recycling of carbon rich waste into compost suitable for arid soils.

Sustainability itself is not a new concept in agriculture. In fact, in 1990[2], the U.S. Congress defined sustainable agriculture as farming practices that, over the long-term:

- Satisfy human food and fiber needs
- Enhance environmental quality and the natural resource base upon which the agricultural economy depends
- Make the most efficient use of nonrenewable resources and on-farm resources
- Integrate, where appropriate, natural biological cycles and controls
- Sustain the economic viability of farm operations
- Enhance the quality of life for farmers and society as a whole

The Food and Agriculture Organization of the United Nations (FAO)[3] further describes the following five criteria for agriculture to be truly sustainable:

- Resource efficiencies
- Conservation, protection, and enhancement of natural resources
- Protection and improvement of rural livelihoods, equity, and social well-being
- Enhanced resilience of people, communities, and ecosystems
- Responsible and effective governance

While exact definitions of sustainability can differ, a common thread is striking a balance between economic, environmental, societal, and resilience factors as they pertain to agriculture.

For the United Arab Emirates, a country that is food secure, but with limited water resources and an environment harsh for agriculture, sustainable agriculture is interlinked with the security of future food supply. For this purpose, the UAE government recently appointed a Minister of State for Food Security, with the vision to make the UAE a world-leading hub in innovation-driven food security. The Minister aims to do so by championing trade facilitation and enabling technology-based production and supply of food. In this regard, the National

[2] "Sustainable agriculture" was addressed by Congress in the 1990 "Farm Bill" [Food, Agriculture, Conservation, and Trade Act of 1990 (FACTA), Public Law 101-624, Title XVI, Subtitle A, Section 1603 (Government Printing Office, Washington, DC, 1990) NAL Call # KF1692.A31 1990].

[3] http://www.fao.org/sustainability/en/

Strategy for Food Security launched in 2018 determines the optimal elements of a national food basket based on production capacity, processing requirements, nutritional needs etc. and sets the initiatives to be followed to meet a set of supporting strategic goals anchored on diversification of supply, alternative supply sources, technology-enabled enhancement of local production, international trade links.

With this in mind, in order to identify and optimise for truly sustainable solutions, it is important to first consider the challenges common to agriculture across all arid regions. Some of these hurdles are physical limitations defined by the inherent aridity of the climate, whereas others stem from logistical limitations (e.g. the lack of developed infrastructure or high-tech workforce that limits the immediate feasibility of certain technological innovations). These include:

Technological challenges. The inherent aridity of these difficult-to-farm regions limits the natural productivity of the land. Specifically, technological innovations often target one or more of the following properties of arid regions:

- **Soil quality.** Soils in arid regions are often characterized by dry, often sandy consistency, which, due to extreme porosity, cannot absorb and retain water for plant uptake. In addition to the structure, soil composition also tends to be saline (high sodium content, exacerbated by repeated irrigation) and alkaline (high pH, usually caused by presence of calcium carbonate, limiting bioavailability of minerals). These conditions[4] combined with the high insolation common to soil surfaces also limit the presence of sub-soil ecosystems needed to maintain and promote plant growth. Farmers often supplement the soil with additives, fertilizers, and chemicals, which can leach into groundwater over time.
- **Water availability.** Most arid farming practices rely on water recycling, desalination, and drip irrigation to grow edible crops. In terms of sources of freshwater, arid regions experience very little rainfall, leading to limited availability of groundwater with low replenishment rates. Further, repeated irrigation increases the salinity of groundwater, often to the point where it is no longer suitable for farming. Additionally, high evapotranspiration rates and sandy soil textures can result in water losses in an open-field setting; farmers then compensate for these losses by increasing irrigation rates. Water recycling and desalination both treat unsuitable water with a combination of membranes and osmotic pressures to produce usable water; however, these processes are expensive and energy-intensive.
- **Air quality.** High temperatures result from very high insolation typical of arid regions. High insolation for 8-10 hours per day can dry out soils and plants due to evapotranspiration. Furthermore, intense light exposure outside the usable spectrum for photosynthesis (e.g. UV rays) can damage plant cell structures, thus limiting growth and yield. In desert conditions, severe wind and sandstorms can physically harm plants in open-field settings. In urban regions, pollution from cars and industry could also play a role in creating sub-optimal growth conditions.

Economic challenges. The pervasive nature of arid climates means that a broad cross-section of countries, regions, population densities (urban vs. rural), and purchasing power of communities are solving for arid farming. Economically advantaged regions can afford to test and implement complex solutions at large scales (e.g. Japan's "Grandpa Dome" dynamic hydroponic farm, in the shape of a circle), though upfront capital investment may still prove unfeasible. For example, urban farming solutions will often require not only upfront capital to build, but also high operational costs (energy, lighting, electricity, water), as well as added insurance to cover the building in case of malfunction. While technological innovations abound, low-tech or creative business model solutions (e.g. community rentals of expensive farm equipment) are often a better fit when considering regional constraints on production, transportation and storage infrastructure, capital, and the availability of qualified technicians.

[4]https://www.ncbi.nlm.nih.gov/pubmed/28593197

CLIX

The Climate Innovations Exchange (CLIX), a core element of the Youth 4 Sustainability organized under the umbrella of ADSW, is another vehicle to promote innovation in sustainability in a wide range of fields. CLIX is aligned with the UAE Ministry of Climate Change & Environment strategy to enable the sourcing, funding and commercialization of climate change solutions and technologies.

CLIX functions as a unique platform connecting entrepreneurs and investors from around the world, exchanging ideas and enabling capital flow to innovative investment opportunities.

This year, the expanded CLIX programme has received a record 811 applications from across 83 counties in categories including Sustainability in Future of Food & Agriculture, Space, and Future of Energy.

Catalyst

Masdar's contributions to innovation in sustainability also include tangible support to innovators and entrepreneurs through ventures such as 'The Catalyst'. As the region's first technology startup accelerator focused on sustainability and clean technology, 'The Catalyst' aims to accelerate the development of viable technology businesses through funding, training and mentorship.

Established in partnership between Masdar and BP, the Catalyst will catalyse innovation, entrepreneurship and the development of a knowledge-based economy in Abu Dhabi. Followed by an intense evaluation and business due diligence, Catalyst accepts applications from local and international entrepreneurs with startup projects in the fields of aggrotech, biotech, electric mobility, renewable energy & efficiency, and waste management systems.

Carefully selected startups will receive funding of up to 150,000 USD. This funding is contingent on the startup becoming an entity within award-winning Masdar Free Zone whilst in the accelerator programme. Catalyst provides on-going support including; correct and sufficient legal, office space, ICT, business support, along with assistance on finding clients for their pilot applications through our extensive networks. Our aim is to bring each startup with a profit oriented portfolio to prepare for Series A funding rounds by keeping their headquarters in Masdar City but aiding in expanding their works throughout the world.

Environmental and societal challenges. Resource efficiency and environmental maintenance are of utmost importance given the limited availability of natural resources in arid farming. These are closely interlinked with societal challenges, particularly in poorer decentralized agrarian regions. For example, challenges with soil quality lead to excessive use of expensive chemical and nutritive soil adjuvants (e.g. pesticides, manure, nitrogen, phosphorus, and potassium additives) which promote near-term productivity, but can a) increase farmers' costs and debt, and b) leach into groundwater, and negatively impact soil quality over time. Additionally, single-crop farming is still practiced in many regions and can deplete nutritional value of soil. However, crop rotation and other "agroecological" methods of farming require access to a wider range of seeds, and knowhow on how to plant and use these crops. Water presents another set of challenges; rural residents often need to travel many kilometers on foot just to retrieve freshwater to sustain a family. Despite this challenge, due to overly porous soil structures, many irrigation techniques still result in wasted water. Some arid regions rely on desalinated water to irrigate edible crops, as local groundwater is too saline to sustain plant growth. Water treatment, particularly desalination, is highly energy intensive, expensive, require infrastructure, and often economically viable only at very large scales. Low-tech solutions (e.g. plastic films, lined or drip irrigation) offer a lot of promise, but can also lead to litter.

While solving for physical limitations of arid farming, entrepreneurs, investors, and regulators need to work together to create frameworks, incentives, and education programs that allow farmer-led initiatives to lead communities to form sustainable farming solutions. In countries with higher purchasing power, governments need to carefully consider legislation and incentive structures that will nurture development of higher tech solutions, designing with sustainability in mind – even if this means short-term losses in favor of long-term return on investment (ROI). However, though policy and regulation is of utmost importance in the future of this field, the focus of this paper will be on current and future technologies, their benefits and drawbacks in solving for sustainable arid farming.

Zayed Sustainability Prize

The Zayed Sustainability Prize is the UAE's pioneering global award for recognising sustainability pioneers driving impactful, innovative and inspiring solutions across five categories: Health, Food, Energy, Water and Global High Schools.

Established in 2008, to honour and continue the sustainability and humanitarian legacy of the UAE's founding father, the late Sheikh Zayed bin Sultan Al Nahyan, the Prize's 66 winners have directly and indirectly impacted the lives of 318 million people, worldwide.

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The Food Category recognises solutions that provide access to safe and affordable foodstuff. These include solutions addressing challenges in hunger and malnutrition, sustainable food security systems, or increasing agricultural and livestock productivity.

Resilience. In light of climate change, civil unrest, and market volatility, it is important to design solutions[5] that can withstand changing conditions – particularly in situations where large capital installations are required. While arid regions are unlikely to suddenly become tropical rainforests, seasonality and the degree and nature of the aridity will likely change over time, as will the incidence of severe weather incidents. Many rural agricultural communities rely on deep historical knowledge of the region's cyclicality to plan planting, watering, harvesting, and crop rotation cycles; increased swings in weather will affect yield, with a ripple effect on livestock, food stockpiles, and thus financial security. On the other side, increased volatility in food prices due to catastrophic events (political, market, or environmental) will also affect producers and buyers throughout the value chain, and end consumers may not have a way to cope. Technologies, business models, and solutions that dampen the impact of these near- and long-term volatilities will be critical – especially as populations continue to grow.

In reviewing key technologies and solutions deployed and under development in arid regions around the world, understanding the key benefits and risks to each is important in matching solutions to the appropriate conditions. Defining sustainability as a balance between techno-economic, environmental, societal, and resilience factors lends itself to a simple framework for evaluating the viability of farming solutions across arid regions:

Assessment rubric:

Metric	Description	Low	Medium	High
Technological value	How well does the solution address known physical challenges with soil, water, and air?	Performs poorly on all three challenges	Address one, but exacerbates other physical challenges	Addresses one or more physical challenges without negatively affecting others
Economic value	How expensive or complex is the solution? To what extent does it rely on existing infrastructure?	Prohibitively expensive expect in niche scenarios	Solution is complex or costly but with high ROI	Versatile solution with low CAPEX & OPEX and high ROI
Environmental/ societal value	Is the solution making the best use of resources without putting a strain on the environment or society?	Inefficient and/ or critical negative impact on society	Somewhat efficient resource use with some non-critical risks to enviornment or society	Efficient resource use with a positive impact on society and enviornment.
Developmental maturity	Is the solution already commercially deployed, or still in developmental stages?	At concept or laboratory / small pilot scale, with limited information on commercial cost factors	In commercialization stages, with large pilots or initial commerical projects in some regions	Fully mature, with large-scale commercial operations in multiple regions
Resilience	Is the solution designed to stand up to changes in climate, population growth, new or different degrees of external stresses?	Designed to withstand only current condition	Can be adjusted for some, but not all likely long-term changes	Highly resilient solution

[5]https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6013986/

Sustainable Agriculture for Arid Climates

INNOVATIONS IN OPEN-FIELD AGRICULTURE

- Irrigation
- Soil enhancement
- Genetic modification and crop breeding
- Crop storage
- Digital solutions and novel business models

Irrigation

In arid regions affected by low water availability, a vast majority of the water used in agriculture applications is desalinated water. In the Middle East alone, availability of brackish water from the Arabian Sea and the Gulf Sea constitutes an ideal resource for desalination. However, desalination is an energy-intensive process that requires optimisation of various parameters, such as intake water quality and saline discharges, which can heavily affect groundwater and soil conditions.

As an alternative to desalinated water, reuse of treated waste effluents as a circular source of water for agriculture is also gaining traction. Similarly, more efficient uses of irrigation systems for enhanced water use need to be examined, as current drip irrigation systems can be costly and inefficient.

Key technologies:

Smart irrigation

Smart irrigation systems use real-time measurements of soil conditions (e.g. via satellites or soil probe sensors) combined with data analytics and weather forecasts to regulate the amount of water that is delivered to the crops. This technology not only enables full control over water dosing, but also provides great insight on crop health status.

Overall, smart irrigation platforms have demonstrated water savings ranging from 30% to 50%, as well as yield increases ranging from 11% to 30% compared to fields without irrigation management systems. In the UAE, a smart irrigation pilot project was conducted in AlQuran Park, revealing water savings up to 40% compared to incumbent systems. Overall, the smart irrigation landscape is crowded with dozens of developers. Key examples include big firms like Mexichem (Mexico) and Jain Irrigation (India), but also small companies like SemiosBio (Canada).

Smart irrigation platform from Chilean company Wiseconn

Most of these companies operate on a for-profit basis, but startups like MimosaTEK (Vietnam) are also involved in projects to aid developing regions. In fact, the company has helped smallholder farmers in Central Highland areas of Vietnam with an IoT platform for precise irrigation, enabling them to survive through severe water shortages. Similarly, the Institute for University Cooperation has helped Peruvian farmers with an irrigation scheduling system that helps them know when and how much to irrigate.

Subsurface irrigation

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 helps regulate water flow to plants. The diffuser works both with gravity and with conventional water pressure, ensuring that all crops are receiving the water they need efficiently.

Farmer examining a subsurface irrigation system in Tunisia

Subsurface irrigation systems have been tested in trees, shrubs, and vegetables, both in open fields and greenhouses. In southern regions of Tunisia, the approach has proven to keep trees alive during dry periods and to improve olive yields. Overall, the innovation can potentially decrease costs up to 30% and to reduce water usage by 30% compared with conventional irrigation systems.

Some examples of companies developing subsurface irrigation solutions are WaterNSW (Australia), GeoFlow (U.S.), and Toro (U.S.). With regard to non-profit organizations, the Institute for University Cooperation is active with pilot projects in arid regions, such as the aforementioned irrigation trials in southern Tunisia.

Growth containers

Growth containers are special boxes with dedicated compartments for plant growth and water retention. This concept has been developed by company Groasis (Netherlands), which remains the sole developer in the space.

The container creates a water column under the plant by collecting irrigation water, dew and rainwater, and distributes it over a long period of time to minimize evaporation. Thanks to this method, young transplanted plants can receive just enough shallow water while they search for water at sufficient depths to develop a strong taproot, enabling resilience during prolonged drought periods. Overall, this approach claims to reduce 90% in both water usage and costs compared to traditional drip irrigation systems. Thanks to these claims, the device received a Green Tech Innovation award in 2010.

Box Growth concept by Groasis

Zero liquid discharge desalination

Brine disposal is a pain point for inland desalination plants. Nowadays, most desalination plants desalinate groundwater and discharge the brine back into the ground, as this is the most affordable disposal option. However, this strategy is highly detrimental for the local ecology, as the groundwater becomes more saline over time. Other disposal alternatives exist, such as discharging via municipal sewers or using open evaporation ponds, but both approaches face several limitations, such as high land costs, rising fees, and strict regulations.

Zero Liquid Discharge Desalination pilot unit developed by the University of Texas in El Paso.

As an alternative, Zero Liquid Discharge (ZLD) desalination systems are being studied to maximise the volume of water produced from brackish sources while minimising impacts to the environment caused by concentrate disposal. Essentially, ZLD is a wastewater management strategy that eliminates any liquid waste from leaving a facility's boundary. Current ZLD systems include a treatment train with a series of high recovery systems that concentrate feeds to a high salinity before a crystallization step, which converts the brine into a solid material rich in minerals.

ZLD systems have been evaluated at several locations across the globe, with multiple pilots in the U.S. (New Mexico, Texas, California and Florida). These pilot studies have demonstrated overall water efficiencies of 95-99% on brackish groundwater. To date, the high cost of installing ZLD systems has been a major hurdle for adoption, although some inland facilities are considering the shift. For instance, rising disposal costs have forced Texas' largest desalination plant, at El Paso, to install a ZLD plant with startup Enviro Water Minerals to recover 2,000 m3/day of potable water and minerals for sale from waste brine produced at the plant.

While a few incumbents, like GE, Veolia, and Aquatech, dominate the ZLD market, a new crop of startups are addressing key pain-points of cost, energy, and reduction in brine disposal volumes for customers. Advanced thermal system providers, innovative membrane distillation systems, and a group of emerging forward osmosis startups promise to dramatically reduce the overall cost of running ZLD systems. Emerging companies that offer relevant ZLD solutions are Salttech (Netherlands), Phoenix Water (Australia), Osmoflo (Australia), Oasys Water (U.S.) and Trevi Systems (U.S.).

Wastewater reuse

Irrigation of crops with treated wastewater and rainwater is an established practice in various countries. For instance, in the UAE, the Dubai municipality issued a directive on the use of treated wastewater to irrigate non-food crops in residential plots.

Similarly, in EU, the European Commission proposed on May 2018 new rules to stimulate and facilitate water reuse in the EU for agricultural irrigation.

Despite these advances, there are still looming concerns about the presence of pathogens, pharmaceuticals and personal care products in crops irrigated with recycled sewage water. As such, considerable studies need to be made to ensure the safety of irrigation using treated wastewater effluents.

Innovations to watch

Management of water salinity	In coastal regions such as the UAE or Mexico, groundwater has a very high content in salt, which makes aquifers unsuitable for irrigating agricultural lands. Recently, consulting firm Arcadis and KWR Watercycle developed a technology that stops and reverses salinization of water reservoirs by intercepting brackish groundwater.
Cloud seeding to generate rain on demand	Cloud seeding is a technology to enhance the amount of precipitation that falls from the clouds. The technology involves the use of airplanes with special seeding flares, which release salt crystals into clouds to improve condensation and form droplets that could fall as rain. This approach has been explored by the Centre of Meteorology and Seismology in the UAE since the early 2000s, using expertise from NASA and other organisations in its experiments. In the year 2017 alone, more than 50 cloud seeding pilots were conducted in the UAE, claiming that the technology helped generate 10% to 30% more rain. In the same year, UAE researchers filed a patent for a special coating for salt crystals, which is claimed to improve the condensation process in clouds.

Metrics	Comment
Technological value: **Medium**	Alternative irrigation systems and novel methods of water reuse allow for greater water conservation and, in some cases, improved yields. However, crops are still cultivated in existing ground, and hence are still exposed to local soil conditions.
Economic value: **Medium**	Irrigations solutions vary on complexity and affordability, with smart systems and zero-discharge desalination sitting at the high end in terms of complexity and low affordability. Considering that these solutions are more likely to have a greater impact on large-scale systems, their economic value is only moderate.
Environmental / societal value: **High**	Thanks to improvements in irrigation scheduling, labour needs are lower than incumbent technologies. Furthermore, improved water dosing and reuse leads to higher water availability for direct human use.
Developmental maturity: **High**	Numerous large and small companies are offering smart irrigation solutions. Desalination space is also crowded with strong developers and universities, while low-technology solutions (growth box, subsurface irrigation) have a moderate amount of developers.
Resilience: **Medium**	Most irrigation and desalination systems rely on hardware installed in-field, and hence are vulnerable to changes in climate conditions and intake water quality.

SOIL ENHANCEMENT

Soils provide essential ecosystem services and play a pivotal role in climate change, food and water security. Unfortunately, roughly 12 million hectares of soil are degraded every year because of deforestation and poor farming practices. These degraded soils have poor structure, are prone to erosion, and lack the nutrients required to support vegetation or agriculture. Similarly, arid soils which cover ~ 40% of the earth's land surface are also poor in quality and have little agricultural potential. However, unlike degraded soils which are man-induced, arid soils are naturally poor in quality because of geography and climate. There is clearly a challenge but also an opportunity to manage degraded and arid soils to produce more food, preserve precious water and store carbon to combat climate change.

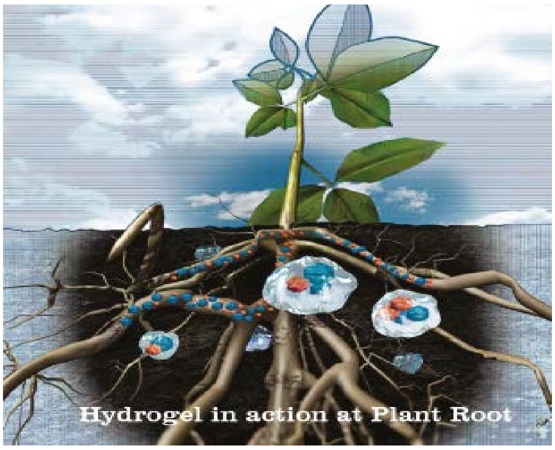
Key technologies

Chemical or material additives for water or nutrient retention

USE OF SYNTHETIC MATERIALS CAN IMPROVE THE PHYSICAL PROPERTIES OF SOIL BY IMPROVING WATER AND NUTRIENT RETENTION CAPABILITIES.

Super absorbent polymers: Hydrophilic polymers can absorb more than 200% of their weight in water, nutrients, and other aqueous chemicals. As the soil dries, the polymer hydrogels passively release the absorbed components into their surroundings.

Super-absorbent polymers adsorb and store water that is normally lost to evaporation or groundwater, reducing the volume and frequency of irrigation up to 50%. The value proposition of these gels has expanded from reduced water use to include improved stand consistency, crop yields, and early vigor. Various types of polymer hydrogels have so far been found appropriate for agricultural use, including starch-graft copolymers and cross-linked derivatives of polyacrylates and polyacrylamides. Most of these polymer hydrogels are environmentally friendly and do not cause problems to the local ecology or the groundwater. In fact, many hydrogels are used to remove trace metals from groundwater.



Super absorbent polymer hydrogels releasing nutrients near the plant root

Some examples of companies operating with super absorbent polymers for agriculture are Chemtex Speciality (India), Ecovia Renewables (U.S.), M^2 Polymer Technologies (U.S.), and mOasis (U.S.).

Nanoclay particles: Clay is an inert material that has been traditionally used as a soil amendment in arid regions like Egypt. Recently, developers have started to experiment with nanosized clay particles. The technology involves separating naturally occurring clay into very fine (200 nm scale) particles and mixing those nanoparticles with water.

The nanoclay particles abrade sand particles already present in the soil, generating additional surface area for fungi to grow on and holding water in the upper soil profile near plant roots. Mycorrhizal fungi typically fail to colonize sandy soils, but the addition of nanoclay allows these fungi to colonize the soil and therefore crop roots, improving crop nutrition and access to water.

Farmer spraying a mixture of nanosized clay and water into an arid soil in Dubai

Currently, the only company developing nanoclay soil amendments is Desert Control (Norway). The company has completed pilot projects in Egypt, China, and Pakistan, and has a very small demonstration plot in Dubai, where the startup grows carrots, peppers, and cauliflower. According to the company, pilot studies have shown an average reduction of water use of 50-65% compared to conventional irrigation methods, as well as more efficient fertilizer use and less runoff. However, the high cost of the technology (fee is between $4,500 and $4,800 per hectare) constitutes a barrier for wider implementation in the short term.

Microbial/biological soil treatments

WATER ABSORBING ORGANIC AMENDMENTS CAN IMPROVE SOIL QUALITY BY INCREASING SOIL MOISTURE CONTENT AND ITS MICROBIOLOGICAL STATUS.

Special compost: Upcycling of organic food waste into specialised soil additives is a relatively nascent field within sustainable agriculture.

Most processes use heat, enzymes and mechanical action to pull the nutrients from food, in order to create compost. The resulting compost has many positive benefits, such as improving soil tilth, organic carbon content, and water-holding capacity.

Founders of UAE-based company De L'Arta

The space is populated by a few small developers, such as California Safe Soil (U.S.) and ZERA Food Recycler (U.S.)

In the UAE, start-up De L'Arta is developing a small scale composting facility for the up-cycling of carbon rich waste into a specialised compost that is suitable for arid/desert soils. The compost has been scientifically designed to target soil problems known to limit agricultural production in arid regions – those being carbon content, texture and fertility.

The company will use these compost in its own pilot farm, combined with other innovations such as precision irrigation. In addition to food crops, the non-edible desert perennial plants will also be cultivated as part of the farming system.

Organic mulches: Mulches are materials laid over the soil to eliminate weeds, slow water evaporation, slowly feed the soil and improve its structure. By creating a spongy texture, organic mulches help the ground to absorb water more easily, reducing runoff during heavy irrigation and improving its ability to recharge moisture levels after periods of dry weather.

Annual results of a fruit tree plantation with and without surface wood mulch in a semi-arid region.

Wood chips are a popular organic mulch option, either in processed form or as byproducts of tree pruning. Other common mulch options are grass clippings, straws, leaves, bark, paper and cardboard. Some types of organic mulches decay quickly, requiring frequent application. Additionally, fast degradation means release of CO_2 and methane into the atmosphere, reducing their sustainability benefits.

Microbial fertilizers: Microbial fertilizers or microbial inoculants contain live cells of specific micro-organisms that are beneficial for various aspects of plant growth. These microorganisms can increase availability and absorption of nutrients like phosphorous or nitrogen, but also improve other aspects like soil aeration or elimination of soil-borne pathogens.

Microbial fertilizers

Key examples of companies developing microbial fertilizers are BioConsortia (New Zealand), Pivot Bio (U.S.), and Pure Ag (Germany).

Innovations to watch

Multipurpose soil conditioning	Companies like TerraCottem (Spain) are developing soil conditioning compounds containing a mix of super-absorbent polymers, but also organic and inorganic nutrients. This integral approach allows to improve soil condition from various angles at the same time, stimulating root growth and leaf development, but also water retention and nutrient dosage. This technology has been proven in-field in arid and nutrient regions like the Sahara desert.
Soil microbiome testing	Microbiome testing kits are used to examine the bacterial composition of soils. These kits allow farmers to gauge the health and productivity of their soil before they begin planting, facilitating decisions about the types of treatments to apply or even which crops to plant. Startups like Trace Genomics (U.S.) and Biome Makers (U.S.) are at the forefront of soil microbiome testing.
Biopolymers and recycled plastics	Biopolymers from plant fibers and recycled polymers from the waste plastic industry can be used to increase water retention capacity. Recycled PET has demonstrated moderate water moisture retention improvements, but research remains at lab-scale.

Metrics	Comment
Technological value: **Medium**	Use of synthetic and organic additives can improve the properties of soil, but full potential is limited by the initial state of the medium. As such, amendments should be seen as a partial fix instead of a complete solution. Full value will rely on a combination with other technologies (e.g. controlled irrigation, analytics).
Economic value: **Medium**	While incumbent soil amendments and fertilizers are widely available and highly affordable, novel methods using synthetic components, nanosized particles or dedicated microorganisms are still expensive.
Environmental / societal value: **High**	Upcycling of organic and other waste into specialised soil additives can simultaneously solve problems derived from waste recycling and subpar soil quality.
Developmental maturity: **Low**	Market of novel soil amendments is populated by various small developers, most of which remain at an early stage. Research in promising disciplines like the soil microbiome is also in its infancy.
Resilience: **Medium**	As changing climate conditions are expected to have a negative impact on soil conditions, the effectiveness of soil amendments is likely to diminish without significant advances in research.

De L'Arta

De L'Arta is a UAE based start-up company with a mission to regenerate and maximise the value of soil to produce local, affordable, high-quality and sustainable food and other natural products in smart cities. De L'Arta plans to achieve this through the implementation of complementary mechanisms involving the up -cycling of specific organic wastes into specialised soil additives, integrating native desert plants as part of the farming system and using smart technologies for precision farming. De L'Arta aims to produce its own compost and showcase soil regeneration practices over a two year period on a 0.2 hectare pilot farm located in Masdar City. The farm is referred to as the "Outdoor Living Laboratory". Furthermore, in support of the UAE's efforts towards a diversified economy, and to help create new local industries, De L'Arta will also be producing fresh and natural skin care range using plants grown from the farm. Three components make up the De L'Arta system in Masdar City:

COMPOST

A small scale composting facility located on the farm has been developed for the up-cycling of carbon rich waste into a specialised compost that is suitable for arid/desert soils. The compost has been scientifically designed to target soil problems known to limit agricultural production in arid regions – those being carbon content, texture and fertility. Green Mountains waste management company in Abu Dhabi (www.greenmountains.ae) is supporting De L'Arta during the pilot project with the collection of specified pure waste streams that are located within a 25 km radius of Masdar City.

FARM

Soil regeneration will be carried out using high application rates to a depth of 50 cm on the farm using the compost developed by De L'Arta. A diverse range of carefully selected food crops will be cultivated on the farm to enhance nutrient cycling, carbon storage, and ecosystem productivity. In addition to food crops, non-edible desert perennial plants will also be cultivated as part of the farming system. Research carried out by founders of De L'Arta demonstrated that desert plants have interesting and unique phytochemical profiles that are potentially valuable in the healthcare and food supplement markets. An automatic (weather controlled) sub-surface irrigation system that delivers water directly to plant roots will be used on the farm. Rain Bird International (www.rainbird.com) is supporting De L'Arta during the pilot project by providing the smart irrigation system and technical support when needed. The combination of using compost and smart irrigation will allow De L'Arta to use at minimum 40% less water than traditional open-field farms in Abu Dhabi. Howard Finley Al-Khaleej (www.hfakagri.com) is also supporting the project by providing the farm with the water tank, landscape plants and labor services in managing the farm. Soil quality and improvements made to baseline conditions will be monitored throughout the pilot project.

SHOP

A formulation laboratory and shop located in Masdar City will be used as De L'Arta's retail outlet to sell natural products developed by the company, those being the compost in the form of small growing kits, and a range of personal care products produced using plants cultivated on the farm. The founders of De L'Arta formulated a range of personal care products using all natural ingredients that are aimed to hydrate and clarify the skin while also providing protection against premature aging caused by environmental pollutants.

De L'Arta is one of three UAE based start-ups that were accepted into an accelerator program developed by the Catalyst. (www.catalyst.ae). Being part of the accelerator program, De L'Arta will receive 50,000 USD in seed investment and mentorship on devising its go-to-market strategy. The pilot project will run for a duration of two years and the long-term goal of De L'Arta is to devise a soil regenerative open-field farming model that can be implemented as an integral component of green zones in smart urban cities.

De L'Arta was founded by Saeed AlKhoori and Dr. Lina F Yousef, both are scientists with academic backgrounds in soil science, chemistry and environmental engineering. The founders are passionate about identifying sustainable solutions to reverse the damage that has been done to the environment.

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GENETIC MODIFICATION AND CROP BREEDING

Demand for food is increasing worldwide, putting extreme pressure on existing varieties that have little hope of keeping up. In arid regions, this problem is exacerbated by the harsh soil conditions and the availability of low-quality water for irrigation, which makes it difficult for crops to survive the growing season. Genetically modified organisms (GMO) and hybrid varieties offer an obvious solution to improve the resistance of existing plant varieties. Each of these approaches has a particular set of advantages and drawbacks.

Key technologies

GMO technologies

AN APPROACH TO OVERCOME THE DRAWBACKS OF GENETIC MODIFICATION IS BY BREEDING NEW HYBRID CROP VARIETIES

Transgenic organisms

Most genetically modified organisms known to the general public are based on transgenic traits. This approach uses genetic material that has been transferred from one external organism to the plant, in order to induce certain favourable traits.

The development of transgenic traits continues to be centred in the U.S. and focuses largely on grower-facing traits like insecticide resistance and herbicide tolerance. Innovation remains largely internal and centers on large corporations, including the big four of Bayer (including Monsanto), Dow DuPont, BASF, and Syngenta, which make up the bulk of patent publications.

Transgenic organisms face strong controversy from the general public. In the past years, two main areas of concern have emerged, namely risk to the environment and risk to human health.

Non-transgenic organisms

Advances in gene editing have made it possible to modify plants using their own DNA material. This has led to the emergence of non-transgenic organisms, which can be manufactured using well-known gene editing tools like CRISPR (known set of DNA sequences used as markers in genetic engineering) or TALEN (enzymes designed to cut DNA strands at specific locations).

Gene-editing provides smaller companies with an opportunity to develop consumer- and industry-relevant traits and varieties that can more easily compete with larger companies' offerings. Example of key smaller companies operating in this space are Cibus (U.S.), Calyxt (U.S.), and Yield10 Bioscience (U.S.)

Genetically-edited organisms face more favourable regulations than transgenic crops. For instance, both the EU and U.S. concluded that genetically edited organisms do not require governmental regulation. However, the general public remains unaware of the difference between transgenic and non-transgenic crops, with most consumers recognizing products as GMO. As such, considerable education towards consumer awareness is needed to advance research of new gene-edited varieties.

Crop breeding

TRADITIONAL BREEDING ENABLES TO CREATE NEW PLANT VARIETIES WITHOUT INTERVENING IN THEIR GENETIC MATERIAL

With advances in genomics and data platforms, it is now possible to identify new traits and to naturally breed new crop varieties without intervening in their genetic material.

The International Centre of Biosaline Agriculture (ICBA) is a world-renowned breeding center in Dubai. The institute is constantly looking for new hybrid seed varieties to be grown in harsh, infertile regions.

A key focus of ICBA is West Asia and North Africa, two of the most water-scarce areas in the world, where agriculture consumes over 75% of freshwater resources. In these regions, most groundwater and river ecosystems are affected by salinity, which is a major constraint for crop production.

In these regions, ICBA is attempting to revive salt-affected farms by growing halophytes, which are climate-resilient and salt-tolerant plants. More specifically, the innovator is looking at key crops such as barley, triticale, fodder beet, pearl millet, sorghum, safflower, and quinoa. By growing such crops using saline water, the institute seeks to improve the livelihood and sustainability of small-scale farms in harsh regions.

ICBA - Salt-Tolerant Crops Farmer Training

Metrics		Comment
	Technological value: **High**	Enhanced crops have increased stress-resistance and can survive under adverse arid conditions, potentially solving pressing issues arising from global food supply instability and climate change.
	Economic value: **High**	Considerable R&D effort and regulation barriers need to be surpassed to accelerate discovery of new varieties. However, once in the market, the economic benefits of improved yields and increased resistance are extremely high.
	Environmental / societal value: **Medium**	Controversy regarding modified organisms will remain a key societal barrier for years to come.
	Developmental maturity: **Medium**	While transgenics and hybrid breeds are technically mature, new technologies like CRISPR and TALEN remain at an early stage. Similarly, advances in sequencing technology and data analytics are still being translated to the field of crop breeding.
	Resilience: **Medium**	Crops with enhanced traits are more likely to withstand harsh conditions compared to incumbent plant varieties. However, considerable R&D effort is needed to create novel varieties in case existing ones fail to survive.

CROP STORAGE

In arid countries, deterioration of horticultural produce occurs immediately after harvest due to severe climate conditions. According to U.N. data, 45% of all fruit and vegetables is wasted before reaching the market. Maintenance of low temperature is key to ensure freshness of both crops and foods. However, in low income regions, limited access to electricity makes refrigerators scarce among households and farms. Even in cases where electricity is available, refrigeration is an energy intensive and expensive process. As such, low-cost innovations are of key importance to ensure that local communities have access to well-preserved food.

Low tech solutions

LOW TECH CROP STORAGE SOLUTIONS DO NOT REQUIRE ANY TYPE OF ENERGY INPUT, AND CAN BE BUILT USING READILY AVAILABLE MATERIALS. THESE SOLUTIONS RELY ON PHYSICAL PHENOMENA TO MAINTAIN THE TEMPERATURE OF CROPS WITHIN APPROPRIATE VALUES, AND CAN BE IMPLEMENTED IN DEVELOPING REGIONS.

Zero energy cool chambers (ZECC)

Considering the acute energy crisis and the lack of cool storage facilities in rural areas, ongoing efforts are being made to develop low cost and low energy storage solutions.

One key approach in this field is the invention of the zero energy cool chamber (ZECC), a concept that was envisioned in India in the 1980s.

These chambers do not require any electricity or power to operate, and can be constructed by unskilled labour using readily available materials such as bricks and sand.

Zero Energy cooling chamber demonstrated at Horticultural farmer day event.

Chambers are constructed with a double brick-wall structure. The cavity is filled with a sand bed and the walls are soaked in water. Inside the chamber, cooling takes place via a natural phenomenon known as evaporative cooling. Basically, when air passes over a wet surface, water evaporates into air raising its humidity and same time cooling the bed.

Example of a Zero Emission Fridge in a subsistence farm in Mozambique.

Overall, cool chambers can reduce temperature by 10-15^{0}C and maintain a high humidity (95%), therefore increasing the shelf life and quality of horticultural produce. Thanks to this approach, farmers from arid and tropical regions can store harvest of several days, minimising food waste and reducing reliance on middlemen.

In Africa, a similar concept of chamber has been proposed, known as the Zero-Emission Fridge for Rural Africa (ZEFRA). The fridge is essentially a seed storage silo built with local materials, such as woven bamboo encased in clay. This low-tech approach enables to seal seeds in a nearly hermetic chamber. Besides, it also contains herbal insect repellents and mouse traps to prevent seeds from contamination.

Solar powered tent by Wakati

To date, most zero-energy cool chambers have been part of non-profit projects by universities (Ehime University) and NGOs (HELVETAS Swiss Intercooperation). Recently, a start-up named Wakati (Belgium) developed a for-profit version of a ZECC chamber. The product is essentially a pop-up style tent, made of airtight fabric that contains the microclimate during the storage.

The tent contains a small solar panel (10 W) to create a high humidity atmosphere by ultrasonic evaporation, as well as an electric corona discharge to create ozone. The tent can preserve between 200 kg and 1000 kg of food using only 1 litre of water per week.

High tech solutions

AS OPPOSED TO ZERO-EMISSION COOLING CHAMBERS, HIGH TECH CROP STORAGE FACILITIES RELY ON REFRIGERATION UNITS TO MAINTAIN A MORE EFFECTIVE TEMPERATURE CONTROL FOR CROPS.

Solar-powered, off-grid refrigeration units

Aside from evaporative cooling, crop storage can also be achieved with conventional refrigeration units. One way to overcome the high cost and high energy requirements of conventional fridges is to use renewable energy as a source of power.

In Nigeria, start-up Cold Hubs is developing an off-grid storage warehouse for perishable food crops. The unit uses roof-mounted solar panels that store energy in high-capacity batteries which feed an inverter, enabling 24-hour refrigeration inside the cold room. This innovation can increase shelf life from 2 to 21 days. The company targets nutrient loss and food waste in rural farming regions of developing countries. In order to make the service affordable and attractive for farmers, the company offers a flexible pay-as -you-store subscription model.

Logistics

BESIDES STORAGE OF HARVESTED CROPS, TRANSPORTATION OF PRODUCE FROM FARMS TO END USERS REQUIRES CAREFUL TEMPERATURE CONTROL TO ENSURE THAT VEGETABLES ARRIVE IN FRESH CONDITIONS. THIS IS A PRESSING REQUIREMENT AS 40% OF GLOBAL GOOD FOOD GETS WASTED DURING STORAGE AND DISTRIBUTION. IN COUNTRIES THAT RELY HEAVILY ON FOOD EXPORTS AND IMPORTS, MAINTAINING THE COLD CHAIN CAN BE PARTICULARLY CHALLENGING. THEREFORE, INNOVATIONS IN FLEET TRANSPORT AND WAREHOUSE INFRASTRUCTURE ARE NEEDED TO MINIMIZE FOOD WASTE IN TIMES OF SCARCITY.

Cold chain management

Cold chain facilities need to be strategically located at interchange and import sites, maximizing ease of access and reducing delays in the movement of food products. Recently, the UAE inaugurated a major cold chain facility in Dubai South. The warehouse comprises various chambers and uses a unique ammonia refrigeration system to accommodate temperatures as low as -25^{0}C.

Besides availability of advanced warehouses, cold chain management requires complex transportation logistics, which include real-time monitoring of parameters like temperature and humidity in trucks and containers. These innovations require considerable planning and investment, but are key to ensure reliable supply of both food and medicines.

Innovations to watch

Real-time monitoring of perishable foods	Besides offering real-time monitoring of temperature and humidity in transportation trucks, start-ups like FreshSurety and C2Sense also offer chemical sensors that detect concentrations of gases that are released when perishable food rots. This information is critical to indicate remaining shelf life of perishable food, which can greatly reduce food waste during storage and transportation.

Metrics	Comment
Technological value: **Medium**	Despite being technologically simple, crop storage solutions can significantly improve the shelf life of produce, which is a major issue in arid regions. However, storage systems are inherently limited to post-harvest stages, and thus have no influence on aspects like soil quality, water availability or agricultural yield.
Economic value: **High**	Storage solutions can be adapted for both developing and developed regions. In both cases, the economic benefits of reducing food waste are enormous, as 40% of the global food supply is currently lost as waste.
Environmental / societal value: **High**	Improved crop storage solutions allow farmers from threatened regions to store harvest for several days, minimising food waste and enabling them to sell produce at a reasonable pace. This enables small communities to reduce dependence on middlemen and to prosper economically.
Developmental maturity: **Low**	Low-technology solutions like ZECC chambers are still in their infancy, with most projects being developed by NGOs. More advanced cold chain management solutions, while technically mature, remain at a moderate stage of implementation in most developed countries.
Resilience: **Medium**	Crop storage solutions will gain increasing importance with threatening climate conditions. However, harsher climates will impose an upper limit to what can be achieved with low-tech refrigeration solutions.

DIGITAL SOLUTIONS AND NOVEL BUSINESS MODELS

Broadly, digital agriculture refers to the application of sensors, connectivity, and analytics to provide a benefit to end users. Multiple assets of agriculture can be connected, including crops, soil, weather, equipment, animals, and the farmer themselves.

Over the past few years, digital agriculture has been lauded as a breakthrough and transformative technology. Despite the consistent hype, digital agriculture has struggled to gain a footing, as many technologies show a poor alignment to end applications.

While some digital solutions can be too advanced for impoverished regions, there are technologies that can offer great value to countries and governments in arid regions, for instance by helping them map which areas are viable to grow certain crops. At the farmer level, these solutions can assist in more precise irrigation recommendations and by reducing chemical and fertilizer usage, which can have a direct impact in the quality of both crops and groundwater.

Key technologies

Aerial imagery

Arid countries are characterized by low availability of arable land. In the UAE alone, arable land accounts only for 0.45% of the total area of the country. In such conditions, it becomes increasingly important to monitor the state of fields in real-time to optimise the efficiency of the land.

Example of aerial imagery data providing insights on crop health

Drones and satellites include advanced cameras to capture high-resolution images of fields from an aerial perspective. Combined with suitable analytics, these images can be used to determine multiple aspects of crop health, including water stress and disease. Additionally, aerial images can be used to scout for new arable lands based on data such as soil fertility and salinity, but also on geographical aspects like windbreak areas (which provide crops with shelter from wind and soil erosion).

While the cost of drones with advanced cameras (~$20,000) is prohibitive for single farms and rural areas, these aerial platforms can be employed by governments and farm cooperatives to collect valuable data.

One example of this holistic approach can be found in the UAE's Ministry of Climate Change and Environment's initiative from 2018 to map agricultural areas using unmanned aerial vehicles (UAV). By combining multiple data inputs across the country (e.g. soil health, number of greenhouses, availability of wells, etc.), the ministry aims to create an accurate agricultural database that supports decision making and forward planning.

Key developers of aerial mapping using drones are Gamaya (Switzerland), Precision Hawk (U.S.) and MicaSense (U.S.). On the other hand, key providers of aerial imagery from satellites are Planet Labs (U.S.), Maxar (U.S.), Earth-I (U.K.), and Astro Digital (U.S.).

Weather stations and crop sensors

While there is plethora of weather forecasting and information services available, generating real-time local data can be invaluable to facilitate more informed crop management decisions. This is particularly relevant for arid and semi-arid regions, which can capitalize on anticipating rainfalls and optimise irrigation practices.

Solar-powered weather station with multi-purpose sensing capabilities. Developed by Arable Labs

Innovation in weather stations has come a long way from bulky and expensive devices with limited functionalities. Nowadays, novel developers like **Arable Labs** (U.S.) have ideated small, solar-powered sensors that can measure multiple weather parameters like air temperature, humidity, and rainfall, but also complex crop features like evapotranspiration, photosynthesis rate, and plant chlorophyll content.

These sensor probes are relatively inexpensive (~$600) and only require one probe per field. When combined with software platforms, they can store crop and weather information and build long-time recordings, enabling growers to benchmark which practices work best in specific seasons or conditions, and alerting them on optimal times to perform irrigation or harvest crops.

Apart from Arable Labs (U.S.), numerous small and large players are offering combined sensor-and-analysis platforms for outdoor crops. Some key examples are Evja (Italy), Digital Harvest (U.S.), Davis Instruments (U.S.), and aWhere (U.S.).

Software platforms

Information from aerial images, weather stations and crop sensors can be useless without a platform that interprets data. For this reason, most companies offer a software that aggregates data from multiple categories into prediction models, providing the end user with agronomic or enterprise guidance via interactive apps or dashboards.

Relevant startups offering data aggregation platforms are OnFarm Systems (U.S.), Granular (U.S.) and Farmers Edge (Canada).

Innovative business models

Many companies in digital agriculture sell hardware (sensors) at a given price point and charge a fee for their software services.

Recently, companies developing costly equipment like UAVs and hyperspectral cameras have pivoted from selling from hardware device sales to providing software-as-a-service (SaaS) platforms. These initiatives are particularly interesting for impoverished regions, governments and farm cooperatives, which can simply purchase software subscriptions and have access to invaluable data on crop health and land status.

Another interesting initiative within digital solutions is the lease of equipment between farmers. In France, the start-up WeFarmUp created an app that allows farmers to lend costly equipment to other farmers at a specific rate per hour. This initiative can help

Farm equipment rental app by French company WeFarmUp

minimize risks when purchasing costly farming equipment like tractors, robots, or drones. In impoverished regions, sharing advanced equipment via an organized model can help communities get involved with more precise agriculture practices and contribute towards more sustainable development.

Innovations to watch

Lower cost spectral cameras	Cameras used by drones and satellites to obtain aerial images are usually multispectral or hyperspectral cameras. These devices are able to divide the visual spectrum into multiple bands, enabling to identify the status of crops and lands with high accuracy. These cameras are often very expensive (~$5,000 for multispectral cameras, >$20,000 for hyperspectral devices). With advances in electronics, the cost of these cameras is going down progressively. In fact, some companies are trying to implement multispectral cameras into smartphones. As such, it is only a matter of time before these cameras become affordable for general use in drones and consumer devices.
Microwave sensing	Many satellite images offer high accuracy to determine crop health and land status. However, cameras struggle to obtain images in the presence of clouds. Giants like BASF are exploring microwave as an alternative to this problem. While the resolution of microwave sensing remains lower than that of other satellite sensors, its capabilities are not impeded by cloud cover, and its accuracy rivals that of direct soil measurements.
Robots for harvesting and weed control	Autonomous robots can assist or replace a portion of manual labor in tasks like crop harvesting, weed eradication or pest control. The cost of these robots remains prohibitive (~$80,000) and is unlikely to provide benefits to arid regions (e.g. due to lower problems with weeds, abundance of manual labor, etc.). However, use of robots can be valuable for high-value crops grown in controlled environments. For instance, robots have proven benefits in detecting and harvesting ripe strawberries, which can actually be grown in controlled environments in the UAE.

Metrics	Comment
Technological value: **High**	Use of advanced imaging and analytics can help optimise most farming practices, including irrigation, crop health monitoring, fertilizer dosing, and crop harvesting. Applicability is not only restricted to open fields, as analytic platforms can serve similar purposes in indoor farms.
Economic value: **Low**	Most digital solutions are prohibitive for rural communities and arid regions. Although novel business models (leasing, software-as-a-service) can soften the capital burden of digital products, achieving profitability in low-yield areas will be difficult without incentives or subsidies.
Environmental / societal value: **Low**	Digital solutions can help reduce laour, improve water dosing and increase crop yields. However, the benefit for developing regions is low, as there is a wide gap between immediate needs of the population and added value provided by advanced technical solutions.
Developmental maturity: **High**	Market is crowded with dozens of strong developers, both for advanced sensors and analytic platforms.
Resilience: **High**	Most digital solutions are essentially advanced monitoring and scheduling tools. As such, they are expected to be resilient to changing climate conditions.

SEAWATER ENERGY AND AGRICULTURE SYSTEM (SEAS) – INTEGRATED PRODUCTION OF SEAFOOD AND HALOAGRICULTURE-BASED SUSTAINABLE AVIATION FUEL (SAF) IN LINE WITH THE FOOD-WATER-ENERGY NEXUS

The Sustainable Bioenergy Research Consortium (SBRC) was established in Abu Dhabi in 2011 as a not-for-profit research consortium to advance the aviation industry's commitment to sustainable business practices by developing technology with the promise of producing a clean, alternative fuel supply. The SBRC was founded by Masdar Institute (now part of Khalifa University of Science and Technology), Etihad Airways, The Boeing Company, and Honeywell-UOP. Since then Safran, GE, ADNOC Refining and Bauer Resources have joined. A key part of its research activity has been the development of a large-scale research program on alternative fuels derived from halophytic (saltwater tolerant) plants, called the Seawater Energy and Agriculture System (SEAS).

The SEAS platform is the SBRC's flagship project, conceived as an integrated and holistic approach to producing biomaterials and bioenergy leveraging marginal resources (i.e., non-arable land and seawater) and renewable energy sources (i.e., solar). The development of such frontier bioprocesses relies on a long-term R&D program based on the SBRC Systematic Research Agenda, which fosters innovation via its academic partner (Khalifa University of Science and Technology) and aligns itself with the UAE national goals for the development of a knowledge-based economy. By enabling commercial-scale production of biomass feedstock, the SEAS platform can anchor a complete Industrial Ecology network for the supply chain of Sustainable Aviation Fuel (SAF) production in the UAE.

The SEAS combines an integrated system of aquaculture, halo-agriculture, and halo-agroforestry, to produce sustainable biofuels for aviation and other socio-economic relevant outputs, such as seafood. In the system's operation, water is pumped from the sea to supply the aquaculture ponds to grow shrimp and finfish. The nutrient-rich water that leaves this subsystem is used to irrigate and fertilize Salicornia fields, where these salt-loving (halophytic) plants that are capable of growing in arid land with saltwater irrigation will be harvested for their oilseeds. Downstream processing of these oilseed extractives can later be converted into SAF. The leftover seed meal can be used as feed for the fish and shrimp, or as a source of protein for animal feed. Finally, the effluent coming from the Salicornia fields will be channeled to mangrove swamps, which filter the water before it reaches the sea again. The mangroves also act as a carbon sink due to their extensive root structure, and together with its biomass may be valorized via carbon offset credit mechanisms, and when reaching a large enough planted area, can be managed in a silviculture scheme. A schematic representation of the whole concept is seen below.

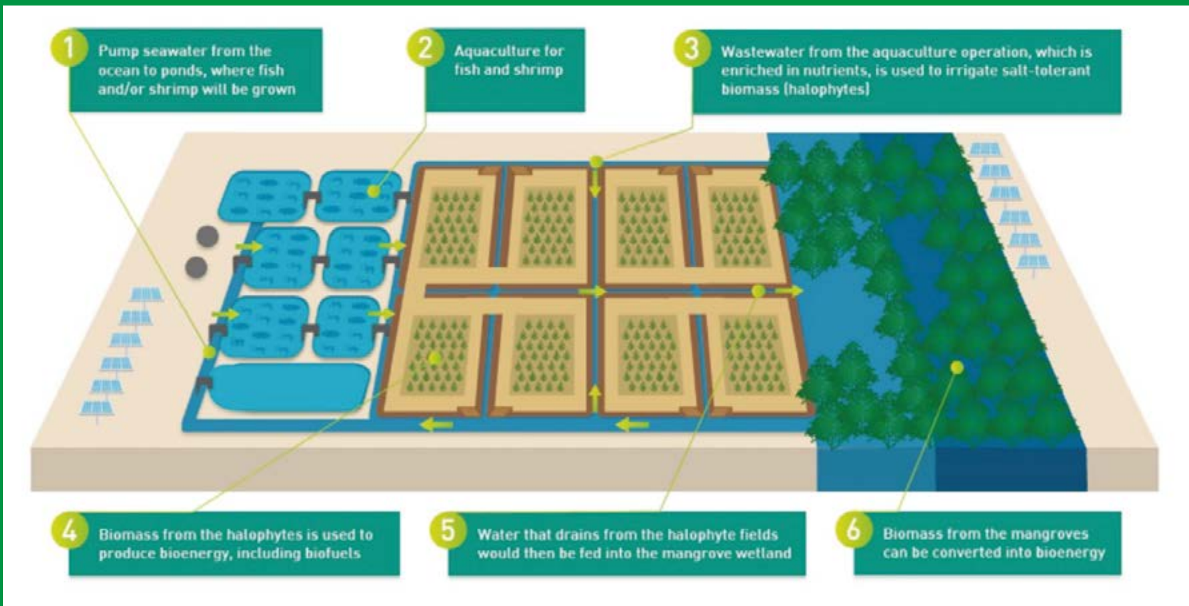


Figure 1: General schematic representation of the SEAS concept.

In its current implementation, the SEAS platform is conceived as a zero- to low-cost SAF feedstock production system. This is achieved by decoupling the economic viability of the platform from the revenue generated by the sale of the oilseed biomass. In the SEAS platform, the revenue driver is the aquaculture unit operation, with other potential revenue streams available in the mangrove halo-agroforestry unit. This way, the SEAS-produced feedstock does not have to be priced similarly to other conventional vegetable oil feedstocks, which provides its market advantage.

In order to be successfully deployed at the commercial level, the SEAS platform is expected to scale-up to its next phase, a 200ha demonstration plant. At this size, the aquaculture portion of the SEAS facility would already be considered a commercial operation, while the salicornia biomass production would be at the feasibility threshold for scalability assessment. Long-term, commercial-scale operations in the UAE could exceed the 100,000ha scale in order to sufficiently supply enough feedstock for SAF production in the UAE.

Sustainable Agriculture for Arid Climates

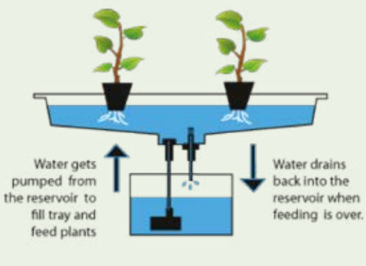
CONTROLLED ENVIRONMENT AGRICULTURE

- Low-intensity greenhouses
- High-tech greenhouses
- Closed or controlled environment cultivation

Controlled environment agriculture

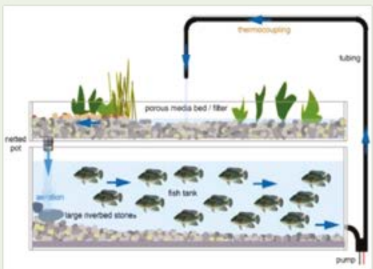
Controlled environment or protected agriculture shields crops from less favorable weather or soil conditions and excessive water evaporation, by creating a (semi-)closed space to cultivate. To eliminate influence from soil variation or groundwater levels, most controlled environment agricultural practices use soil-free cultivation, based on hydroponics or variations thereof:

- **Conventional hydroponics** uses a liquid medium to deliver water and nutrients to growing plants. Commonly, growers use tubing to deliver and extract water around plant root systems grown within a basalt fiber matrix (rockwool). Alternatively, deep water culture systems use large water troughs with plants floating in trays on top.
- **Aeroponics** uses a nutrient-charged, hydrated aerosol to provide moisture and nutrients to plants' roots suspended in an enclosed growth tray. This reduces the water volume and weight in the growth trays, making it specifically suited for stacked growth systems.
- **Aquaponics** is a hybrid of hydroponic plant production and fish farming. Nitrogen-rich fish farm wastewater fertilizes plant roots, while these plants remove nitrogen and other contaminants to allow re-introduction to the fish farm. This is an essentially closed-loop system with minimal water treatment and added fertilisation.



Hydroponics system design

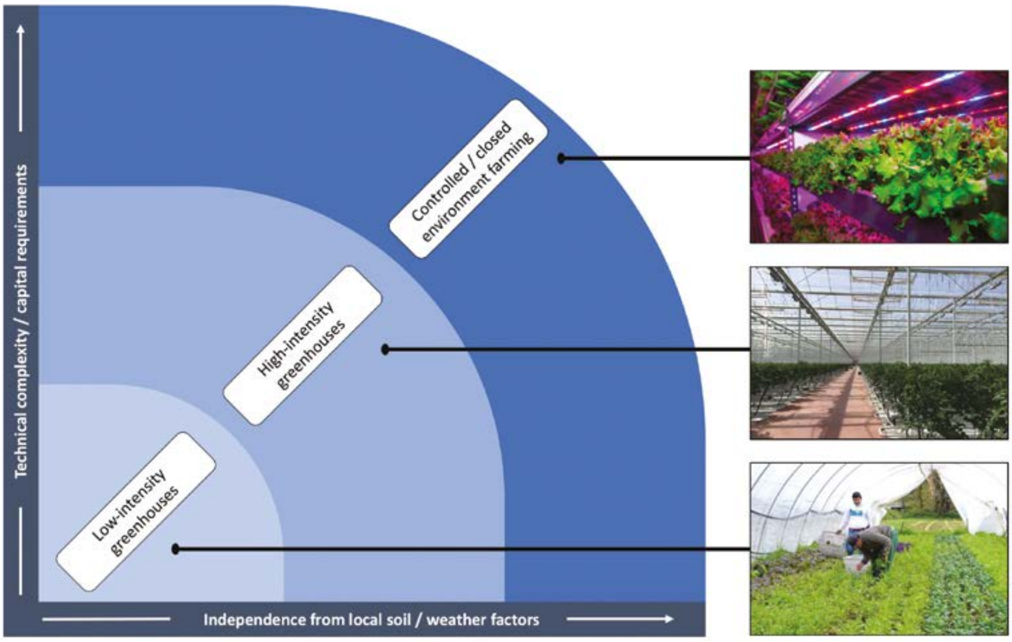
Aeroponics system design



Aquaponics system design

Soil-free cultivation. Sources: sdhydroponics, aerofarms, aquaponicssystems, via Lux Research

Controlled environment agriculture broadly falls in three main categories, classified by the level independence from local soil and weather conditions (e.g. rainfall, temperature, soil nutrients, wind), and the technical complexity or capital requirements. Because of higher upfront capital requirements of controlled environment agriculture, it is generally used for higher-value crops like fruits and vegetables, such as lettuce, strawberries, bell peppers, tomatoes, or decorative plants and flowers.



Growth shelf of Crop One, which partnered with Emirates to supply salad greens. Source: CNN

High-intensity greenhouse in Abkhazia, built by Dutch construction company. Source: Debets Schalke (NL)

Basic, manual irrigated plastic greenhouse producing organic salad greens. Source: Gathering together farm (U.S.)

Controlled environment agriculture broadly falls in three main categories

LOW-INTENSITY GREENHOUSES

LOW-COST SOLUTIONS FOR BASIC PROTECTION

In areas with sufficient nutrient-rich land area, low-cost, low-tech plastic solar films over a hoop frame can protect cultivated soil from excessive solar exposure, rainfall, or winds. Multiple chemical companies produce greenhouse films, including e.g. BASF (Germany), PTTGC (Thailand), or ExxonMobil Chemical (U.S.). Key features include:

- Sunlight is diffused by translucent films to avoid excessive evaporation and/or solar burn on plants, while trapping heat to create more favorable growth temperatures. By applying mulching films, farmers can further reduce evaporation losses and prevent growth of weeds.
- Cover offers rudimentary projection from high winds, rain, or pests, though strength of plastic frame and film is limited in extreme conditions.
- Simple gutters can capture rainfall or dew moisture from the structure, which can be combined with basic irrigation systems.
- Installation of raised racks with soil trays enables more control over soil conditions, albeit at higher cost and complexity.

Globally, the majority of covered, or protected agriculture structures are low-intensity greenhouses: simple plastic-covered tunnels or similar temporary structures, reported at close to 3.5 million hectares in total. While some automation is possible for these structures, tractors or combine harvesters generally cannot fit inside. As a result, labor requirements are comparable or larger than open-field farming, and these solutions are mostly suited for higher-value crops such as fruits and vegetables. Such low-tech, inexpensive plastic greenhouses are most suited for rural areas, and can allow farmers to increase crop yields three-fold compared to open field cultivation, while conserving water.

Innovations to watch

Plastic greenhouse aquaponics	Some farmers in developing regions started farming fish inside plastic covered greenhouses, making use of the increased temperatures to promote growth of fish like tilapia, catfish, or rainbow trout. Bearing resemblance to how Indonesian farmers have grown tilapia in flooded rice fields for centuries, this inclusion of fish farming enables use of aquaponics to boost income of farmers in rural areas.
Dew water re-capture	The Roots Up-University of Gondar (Ethiopia) initiative developed the Dew Collector greenhouse concept. While not commercialized at this time, the concept allows farmers to utilize the cold night air to condense water vapor evaporated during the hot afternoon onto the greenhouse plastic, capturing and reusing it for the plants or as drinking water.
Metal-coated netting greenhouses	Indian non-profit organization Kheyti is developing and co-funding low-intensity greenhouses for small-scale farmers in hot climate zones. These have drip-irrigation systems to conserve up to 90% water compared to non-covered cultivation, and use aluminum coated netting instead of plastic film, to reflect part of the sunlight to reduce the inside temperatures, and protect crops during harsh downpours.

Metrics		Comment
	Technological value: **Medium**	While this addresses water conservation and temperature control to a certain extent, it largely cultivates in the existing ground, leaving it exposed to local soil conditions.
	Economic value: **High**	Simple and relatively cheap solutions, which a farmer can install for a few thousand dollars to increase productivity several-fold.
	Environmental / societal value: **Low**	Compared to open-field, labour needs are similar or even higher if existing farming equipment cannot fit inside the plastic greenhouse. Irresponsible replacement or degradation of plastic films can cause litter.
	Developmental maturity: **High**	Numerous large and small chemical companies in the world produce greenhouse films, some include e.g. light-modifying properties. Thousands of hectares of plastic greenhouses are in use globally.
	Resilience: **Low**	Films have limited lifetime compared to high-tech greenhouses, due to degradation or breakage over time due to high winds, solar UV exposure, and damage from extensive use.

HIGH TECH GREENHOUSES

HIGH-TECH SEMI-CLOSED INDUSTRIAL AGRICULTURE

Semi-closed, glass or transparent polymer-covered greenhouses allow entry of sunlight and some atmospheric air, while offering a high level of control over solar radiation, internal temperature, and air composition. While planting in the ground is possible, most industrial greenhouses use concrete foundations, combined with hydroponics. The closed, highly controlled growth space with solid concrete foundations enables key features such as:

- **Extensive climate control systems,** to control sun or artificial light levels, temperature via heating or cooling systems, moisture, and elevated CO_2 levels to fertilize plants. Energy is often supplied by on-site gas-fueled power systems, which capture emitted heat and CO_2 and channel this into the greenhouse. With technical overlap between greenhouses and building HVAC systems, climate control systems benefit from recent energy efficiency advances in the building energy management sector.
- **High levels of automation,** using fully-automated hydroponics networks, extensive nutrient level and temperature monitoring sensor networks, and often inspection, planting, and harvesting robots.

- **Use of natural predators of pests,** such as the predatory mite *Phytoseiulus persimilis* to control destructive spider mite populations. The enclosed space prevents escape of these predators into the outside ecosystem, while helping to drastically reduce or altogether eliminate use of pesticides.

- **Water recycling.** Plant roots selectively take up specific nutrient ions (e.g. phosphate, potassium), while preventing uptake of e.g. sodium. Reverse osmosis water recycling systems remove excessive salt build-up in wastewater, which can then be supplemented with depleted nutrients and recirculated into the greenhouse.

Dutch HortiDaily High Tech Greenhouse Tour 2015.
Source: HortiDaily via Freshplaza.

Pepper picking robot.
Source: Wageningen University

Globally, close to 500,000 hectares of greenhouses are permanent glass or plastic covered high-tech greenhouses. The Dutch greenhouse horticulture industry is the leader in both high-tech greenhouse productivity and global R&D. Its extensive greenhouse acreage makes it the second largest food exporter by value in the world. Each greenhouse acre yields up to 10 times more lettuce as an outdoor acre, while cutting the need for chemical fertilizers and pesticides by ~95% percent. Together with the leading agricultural University of Wageningen (Netherlands), the greenhouse industry is working to enable zero-water discharge greenhouse systems.

Innovations to watch

Light-emitting diode (LED) lighting	Displaces incumbent sodium-discharge lighting. Besides large energy savings, this enables precise tailoring of the light spectrum and intensity, and even direction from which is shined on the plan. Extensive research, executed amongst others at the Delphy Improvement Centre (Netherlands) shows can promote e.g. faster growth, higher nutrient levels, or better taste or texture in the crops.
Geothermal heat supply	The extensive Dutch "Westland" greenhouse region is piloting deep geothermal wells to heat greenhouses during the night or cold periods, including at the Duivestijn Tomatoes greenhouse complex (Netherlands). The CO_2 fertilisation gas, normally captured from on-site natural gas Combined Heat and Power systems, is instead supplied by carbon capture systems in the nearby Rotterdam petrochemical cluster.
Film-farming	Conventional hydroponics often use basalt fiber as a scaffold for plant root system. Mebifarm (Al Ain, UAE) uses an innovative thin polymer and hydrogel film between the hydroponics tubing and air, which was developed by professor Yuchi Mori. The hydrogel absorbs water and nutrients and forces the plant to develop dense roots closely attached to the hydromembrane surface to absorb the water and nutrients. This technology can save up to 90% of water consumption, reduce fertilizer use by 80%, while the film can protect crops from exposure to pests and pathogens.

Metrics	Comment
Technological value: **High**	Compared to open field, high-tech greenhouses can achieve up to 10-fold or more reduction in water consumption, allows for near full control over air conditions, and addresses soil challenges via advanced hydroponics.
Economic value: **Medium**	Despite high returns from increases productivity, high capital expenses and higher energy consumption costs put high-tech greenhouses out of reach of most rural regions in developing nations.
Environmental / societal value: **Low**	While water consumption can be drastically decreased, energy consumption is several folds higher; integration or renewable energy sources such as solar PV or geothermal heat can offset this, but at high capital costs.
Developmental maturity: **High**	While R&D continues to improve high-tech greenhouses, these are widely commercially deployed. Both development and construction of high-tech greenhouses globally is led by Dutch companies and research organizations.
Resilience: **High**	Solid construction with concrete foundations can withstand adverse conditions and adjust interior to broad range of changing climatic conditions; hurricane resistance is improving with transparent polymer greenhouse development.

CLOSED OR CONTROLLED ENVIRONMENT CULTIVATION

STACKED GROWTH SYSTEMS ENABLING URBAN OR VERTICAL FARMS

Rather than produce food in a consolidated manner for the lowest possible cost per unit and then transport it into cities where demand is high, vertical or urban farming aims to produce fresh foods within the limited space of urban areas. Generally, stacked (vertical) growth racks maximise use of space, to allow medium-scale cultivation within a community (e.g. in or on large warehouses), or small-scale, modular cultivation (e.g. at a shop or house), relying on artificial lighting instead of sunlight. Key features can include:

- **Energy-efficient, low temperature lighting.** While some systems utilize sunlight, most vertical farming setups do not have glass, and need energy-efficient, cool temperature artificial lighting to limit otherwise high energy consumption. Options include induction, fluorescent, and LED lights. LED offers longer lifetimes, high efficiency, and precise control over the emitted light spectrum and intensity to promote plant growth and properties.
- **Climate control,** within the largely sealed growth environment, allows control over moisture, temperature, and CO_2 levels to promote optimal growth of plants. Improvements in energy-efficiencies of climate control systems from the building sector are equally benefitting vertical farming, which largely use similar equipment.
- **Mechanization and automation** to decrease labor loads and increase yields. Equal light distribution is key for optimal plant growth. Often, each layer of a stack has its own lighting system; tall, sunlight reliant systems require rotation of the shelves to equalize exposure. Some setups have growth tray conveyor systems to automatically transport trays to a central planting and harvesting area.
- **Liquid and nutrient management.** Most setups rely on hydroponics, with high levels of sensor monitoring and automation of irrigation, fertilisation, and water recycling,

to maximise growth and prevent biofilm formation or growth of fungi in areas with lower fluid flow or limited light exposure. Some setups may use more elaborate aquaponics to produce both fish and vegetables, or aeroponics to reduce liquid weight in moving growth trays.

- **Chemical-free cultivation** using so-called plant factories, several of which are fully commercially operational in Japan: fully-sealed, highly controlled environments, to prevent any entry of pests, and control lighting conditions, gas concentrations, air flow patterns, nutrient-levels, and moisture to maximise growth without fertilizers or pesticides.

Japan is the global leader in vertical farming, with over 150 operating companies, around half of which are profitable. While few such facilities exist outside Japan at the moment, consumer demand for fresh, local, and chemical-free high-quality produce is increasing. As a result, the emerging industry of vertical farming receives significant interest and notable investments. In 2017, AeroFarms (U.S.) secured $80 million from two funding rounds, while Bowery (U.S.) received $27 million in funding. In July 2018, Emirates Flight Catering (UAE) and Crop One (U.S.) partnered to build a 12,000 sq. m vertical farm, to produce up to 2,700 kg fresh food for Emirates flights. Plenty (U.S.) raised $200 million, with notable backers such as SoftBank and Amazon's Jeff Bezos, and announced a 18,500 sq. m vertical farm in Abu Dhabi (UAE) in August 2018. In December 2018, Agricool (France), which uses hydroponics to grow strawberries, received $28 million from various investors, including Danone Manifesto Ventures, while Seven-Eleven Japan announced plans for a vertical farm facility with a capacity to produce lettuce for 70,000 salads per day, claiming to use 0.25 gallon instead of 34 gallon for one head of lettuce. For modular hyper-local production, solutions include containerized urban farms from e.g. UAE-based start-up Madar Farms' pilot or Freight Farms' turnkey CropBox (U.S.).

Despite clear benefits in transportation costs, labor requirements, and water consumption, vertical farming's high capital and operational costs require price points at or above that of organic produce, limiting feasibility to niche high-income markets. Further, with space and structural limitations, it is best suited for compact or low to the ground growing crops with a short life cycle (e.g. lettuce, peppers) and with high-quality premium pricing (e.g. tomatoes). Highlighting the challenge, only 50% of the farmers reported profitable operations in a recent survey. And while several developers are showing progress, this is offset by others that are less successful. For example, FarmedHere (U.S.) went bankrupt in 2017, before it could complete its 5,500 sq. m facility. Similarly, UrbanFarmers (Netherlands), operating an aquaponics fresh salad and fish restaurant on top of a building in The Hague, went bankrupt in 2018.

Left: Worker inside a Toshiba (Japan) plant factory, housed in a converted clean room building. Inspection of Plenty's first, San Francisco (U.S.) based vertical farm. Source: Businesswire and businessinsider

Innovations to watch

Renewable power supply	Vertical farming's high energy consumption for light, climate control, and automation, detracts from its appeal to its main target market of highly demanding, yet environmentally responsible consumers. As the market grows and allows for higher capital expenditure, players will start integrating renewable power supply, such as rooftop solar PV panels.
Wastewater recycling	As membrane technology for wastewater treatment improves, vertical farms will move more towards compact zero-discharge water recycling systems. In addition, treated municipal sewage water is rich in nutrients; this very problem for discharging into surface water can be a key benefit for plant fertilisation. As sewage treatment systems improve to remove harmful trace contaminants (e.g. pharmaceuticals), this discharge water will become an ideal irrigation water source for urban vertical farms.
Growth optimisation algorithms	With extensive sensor networks, high automation, and exclusion of external uncontrolled weather conditions, vertical farms can leverage machine learning algorithms to optimise growth conditions towards high yield, nutrient levels, or flavor, while minimising energy and water consumption. Examples of developers leveraging artificial intelligence and machine learning are: • Carnegie Mellon University (U.S.) developed a simple stacked shelf vertical farm, equipped with blinking LED lighting; by varying the blinking frequency and light colour, it is researching the impact of light on plant growth. • Keihanna's vertical farm (Japan), which started shipment in November 2018 of up to 30,000 heads of lettuce per day, uses extensive analytic of crops combined with AI algorithms, to maximise growth without pesticides. • Plenty (U.S> / UAE) uses infrared sensors throughout the farm, combined with machine learning to optimise growth conditions, aiming to use these capabilities to expand from current salad greens into affordable, tasty fruits and vegetables. • AeroFarms (U.S.) uses sensors and cameras combined with computer vision and machine learning, to qualify crop health, and adjust growth conditions.

Despite its challenges, the nascent field of vertical farming certainly has a role in the future of fresh food services. It will see more partnerships between vertical farming developers and fresh food restaurants, delivery, catering, or high-end shops, which can tolerate higher prices to offer their customers better quality. However, the best vertical farming companies will be those that are optimised for high-yields and energy-efficiency, are able to scale modular or otherwise, and are able to secure the right partnerships and locations to benefit from on-demand direct delivery without inflating capital costs.

Metrics		Comment
	Technological value: **High**	Vertical farms can exclude all external conditions for full control over air, soil, and water conditions. Inclusion of renewable power sources, water recycling, and growth optimisation algorithms can help maximise productivity.
	Economic value: **Low**	Solutions have very high capital expense and high operating costs, especially if excluding direct sunlight. Produces premium product, but high costs and several bankruptcies make this currently only suited for niche scenarios.
	Environmental / societal value: **Low**	While this supports global megatrends of urbanisation and local production, high costs make vertical farming only suited for high-income countries and consumers, while full automation limits job creation opportunities.
	Developmental maturity: **Medium**	While some facilities are operating commercially and profitable, several bankruptcies also highlight commercial challenges. With ongoing investment and optimisation, this field will continue to mature in the coming ten years.
	Resilience: **High**	Ability to construct vertical farms inside urban warehouses or any other location allows for full exclusion of outside conditions, rendering changing climate conditions largely irrelevant to successful operation.

Madar Farms to Launch a Container Farm R&D Complex

Madar Farms, a UAE based startup, is proud to announce further collaboration with Masdar, focusing on delivering the future of sustainable agriculture to the UAE. Aligned with a directive from the Minister of State for Future Food Security, this pilot project will aim to demonstrate the commercial and technical viability of Controlled Environment Agriculture (CEA) in the challenging climatic conditions of the UAE.

What is CEA?

Controlled Environment Agriculture has been described as part of the Fourth Agricultural Revolution. The basic concept can be thought of as growing fruits and vegetables in a box. Whether that box is a repurposed sea container, as is being used for these initial studies, or a commercial scale insulated warehouse type structure – the key aspect is control. With traditional field agriculture, the grower is at the mercy of the local weather conditions as well as macro level climatic changes. Growing in a controlled environment however, allows the grower to be isolated from unpredictable variables, focusing solely on optimizing plant growth conditions.

مـزارع مـدار
madar farms

How is this different from greenhouses?

Greenhouses have existed in various forms since the 15th century. As technology develops, we are able to better control the various aspects of growing. Current "high technology" greenhouses have the ability to control the amount of light, temperature and humidity inside the growing environment. These greenhouses are typically considered "semi-closed" in that they still allow atmospheric air in, periodically.

With CEA however, sunlight is replaced with highly efficient LED lights, specifically tailored to the growing needs of plants – using the exact wavelengths required for optimal growth. Furthermore, air and water are fully recirculated and filtered, so there is essentially zero wasted water. Greenhouses in this region are typically cooled with evaporative coolers, which consume significantly more water for cooling, than the plants do for growth.

Furthermore, CEA systems are completely closed off to the outside environment – which enables growers to virtually eliminate the risk of pest or microbiological infections. Growing produce in these systems, located close to major population centers delivers maximum nutritional value with minimal environmental impact. The growing environment is under constant electronic surveillance, measuring several data points per minute, facilitating data based analytics, and incremental improvements of growing conditions.

This containerized farming solution will quantify production output, measured against environmental inputs (water and electricity). After gathering data on a variety of crop types, a technology-to-market summary report will be presented to policymakers.

For more, visit www.madarfarms.co - A new container farm will be located just behind Masdar Park, Abu Dhabi and will be open to the public in March 2019.

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