Future Prospects of Vertical and Hydroponic Farming

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Abstract

Today, according to the most recent estimate by the UN, the population may reach 9.1 billion by 2050 due to which food demand is expected to increase to 77% [oESA22]. Nearly 33% of the world's arable land has declined due to desertification and the trend continues with increasing urbanization, pollution, and improper agricultural practices [IU15]. This has had a huge impact on the agricultural sector and if sustainable framing methods are not adopted, we will not be able to produce sufficient amounts of food in the future. This creates the need to look at alternate methods and this is where hydroponic farming comes into play. With growing population and less availability of arable land, vertical framing has been receiving immense popularity as an efficient farming method to meet today's demands. There have been recent advancements in making vertical farming more efficient and they have shown promising results supporting that hydroponic farming stands as a viable solution for agricultural concerns. One example being Singapore where hydroponic farming has been immensely successful in feeding the local population despite having minimal availability of land for production of food. It is essential to adopt ecofriendly methods as climate conditions degrade each day and hydroponic farming proves to be a self-sufficient and sustainable agriculture practice.

1 Introduction

A recent UN report clearly indicates that the world population is projected to increase to 11.2 billion by 2100 which would then increase the demand for food by 59% by 2050 [oESA22]. To make matters worse, both arable land and water supplies are showing an alarming downward trend across the world.

Alarmingly, unsustainable farming practices along with pollution has caused great damage to agricultural land. According to the University of Sheffield's Grantham Centre for Sustainable Futures - "the world has lost a third of its arable land due to erosion or pollution in the past 40 years" [DC15]. This loss

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has occurred due to varying factors such as population growth, climate change, degradation etc. If these factors are not controlled, the amount of arable land available will continue to decrease at a fast rate, leaving no means to practice soil-based farming. Global warming is posing a huge threat too. It is estimated that a 1- degree increase in atmospheric temperature will lead to a 10% decrease in the amount of land suitable for agricultural purposes [Des11]. Most countries have been short-sighted in their approach and resorted to industrial agriculture and monocropping using synthetic fertilizers and pesticides to increase yield, which in turn has proven to be harmful for the soil.

This is not restricted to any particular region but is a worldwide trend. From 2001–2016 farmland in the United States decreased by 2,000 acres every day. The report also shows that, if this trend continues, another 18.4 million acres will be converted by 2040—an area nearly the size of South Carolina [MH22]. According to FAO [SM21], 65% of productive land in Africa is degraded and 45% of the continent's land area is effected by desertification. "Every year, nearly three million hectares of Africa's forests are lost, leading to a 3 percent loss of GDP associated with soil and nutrient depletion," FAO reports. The most recent estimates show that 281.6 million people on the continent, over one-fifth of the population, faced hunger in 2020, which is 46.3 million more than in 2019 [FA21]. According to a report published by The Energy and Resource Institute (TERI) India's GDP in 2014-15 suffered a loss of 2.5% due to land degradation. According to the same report, this is an unsustainable situation as the "The annual cost of land degradation outstrip the total costs of reclamation in 2030" [EI18]. According to FAO [FAO20], "Global cropland area per capita decreased continuously over the period between 1961 and 2016: from about 0.45 hectare per capita in 1961 to 0.21 hectare per capita in 2016."

It is becoming abundantly clear that soil based agricultural systems are not a sustainable practice for the production of food and will not be the solution to the increasing global demands and multiple challenges that are likely to emerge in the future.

Water is the second problematic concern. Let's not forget that the expanding world population, changing dietary habits, moving towards animal products, faulty agricultural practices, climate change, increased water pollution etc. will add to the water problem in our world. Half of the world's population could be living in areas facing water scarcity by as early as 2025 [oESA22]. In developed countries, water consumption for irrigation uses approximately 60% of available hydric resources, while this can reach 90% in developing countries [TA17]. Water is going to be a precious resource in the future. As it is a limited resource, its conservation becomes essential and as a huge percentage of water sources is used for irrigation of agricultural fields, water efficient practices must be adopted especially in places where there is shortage of water. According to the historian Geoffrey Parker- "More recently, climate change has opened new trade routes, resources, and rivalries in the Arctic. And now China, a great power that often appears bent on reordering the international system, is running out of water in ways that are likely to stoke conflict at home and abroad" [AM22]. This is a hint for what may become the future cause of war- water! China, with 22% of the total population of the world has only 6% of the world's total freshwater resources. 2014 statistics from the World Bank indicate that the total renewable water resources per inhabitant is only 2018 cubic meters each year- 75% less than the global average. Water shortage has affected agriculture and residents' lives in northern China [Xin03].

The rapid increase in the population, water shortage, and the decline in arable land and other problems will require a highly efficient agricultural system with a high product yield. Vertical farming popularised in 1999 by Dickson Despommier, professor of Public and Environmental Health at Columbia University, is fast emerging as a good alternative. This unique solution was embraced by countries like Singapore and Japan, which have a very small portion of arable land. In 2009,in Japan there were 35 vertical farming factories in the country [Koz13] and in 2017 this number exceeded 150 [Hau17]. No other country has as many vertical farms as Japan; subsequently, the cost of leafy greens has been reduced extensively by mass production [Hau17]. In Singapore, which has a very limited amount of agricultural land and where 80%of the population lives in apartment buildings, the rooftop spaces became a useful ground for trying vertical farming to meet its growing food demand. Singapore saw rapid urbanisation in the last few decades on account of a massive influx of immigrants which further reduced its arable land and created a huge food supply challenge. A unique private-government collaboration between the Agri-Food and Veterinary Authority of Singapore and Mr. Jack Ng, inventor and founder of a local firm called "Sky Greens" which started commercial operations in 2012, heralded the vertical farming trend in the country which proved to be a game changer. Acknowledged as the "world's first low-carbon, water-driven, rotating, vertical farm" for growing tropical vegetables in an urban environment, Mr. Jack Ng introduced his success story in vertical farming system at the "World Cities Summit 2012" under the slogan "Liveable and Sustainable Solutions" triggering huge interest in this method from across the world.

The United Nations [oESA18]says that by 2050, 68% of the world will live in densely populated urban areas—up from 55% today. Thus, the Singapore case study could be a good example for others to follow to make people more self-reliant in terms of food supplies for their basic needs. Vertical farming has been hailed for a variety of reasons. It cuts through the problematic issue of arable land and makes urban communities self-reliant. Existing vertical farms have shown that if done scientifically, vertical farming has the potential to increase up to ten times the crop yield per acre, when compared to traditional farming methods. It is less reliant on climate and weather variables and can be done year-round. According to the USDA [oA21] vertical farms also help in bringing the food supplies closer to home and reducing the distance the produce travels to reach stores compared to traditional farming method produce. This makes the supplies more readily available and cuts costs, ultimately benefiting the consumer. Vertical farming experts claim that since the farming is done under greater control, best practices of plant breeding, pest management, and engineering can be applied more easily than in traditional farming allowing a more organic and healthier produce.

Vertical farming has three principal techniques: 1. Hydroponics is a technique of growing plants without soil. 2. Aquaponics takes hydroponics one step further by combining the production of plants with the production of aquatic organisms 3. Aeroponics: this method does not use any liquid or solid medium to grow and uses a liquid solution mist with nutrients.

Through this paper, I wish to evaluate the efficiency and sustainability of the first technique - hydroponics, which is fast becoming the foundational method for the other two techniques. I will elaborate on the latest developments in the field and weigh the pros and cons of the method to evaluate its efficacy as the ideal futuristic practice opposed to conventional practice in meeting the growing demand for food across the world.

2 Research Findings

2.1 What is vertical farming and hydroponics?

The greenhouse concept has been around us for many years. Pushed into a corner due to decreasing arable land and other environmental and water crisis, overtime, this concept has also evolved with the advancement in technology and science giving us the advanced and improved version of vertical farming. Vertical farming is the practice of growing crops in vertically stacked layers to ensure higher output in limited space using artificially controlled agricultural environment. Dickson Despommier, Professor of Public and Environmental Health at Columbia University, is credited to be amongst the first scientists to look at vertical farming as a solution to the world's hunger issue. His experiment was initially focused on decreasing the carbon footprint by shortening the distance between production area and consumers. This led to the realization that a high-rise building solely dedicated to cultivating crops can feed a higher number of people than he first assumed. In 1999 he designed a vertical farm on a skyscraper farm that could feed 50,000 people. It was this idea that caught the imagination of others and even governments in countries with limited arable land available for agriculture began to see it as a viable alternative.

Vertical farming is soil less mostly and does not let the variable of natural weather and climate impact production as all growing conditions are artificially controlled. With the aspect of soil being limited eliminated, the numerous problems associated with soil simply do not take place in vertical framing. Less water is used as compared to conventional agriculture thereby making the system water efficient. Due to being indoors, the crops are not damaged by the outside weather conditions and produce a higher crop yield throughout the year. It is a perfect solution for production of food in urbans areas as empty buildings and rooftops can be utilized to practice this method and can also be adopted by families and individuals to produce their own food. New advancements and techniques are being developed to make the system more efficient; for example, the use of artificial lights like LED which is ideal for areas that receive limited amount of sunlight as well as the creation of controlled environment agriculture technology which maintains the required levels of humidity and temperature to create the perfect environment for the crops to grow.

2.2 Techniques of Vertical Farming

Vertical farming can be further broken down into different segments based on growing techniques with different environmental requirements, as shown in figure 1 below.

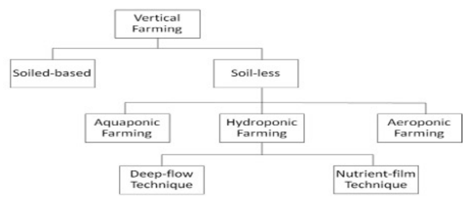

Figure 1: Techniques of vertical farming

2.3 Hydroponic farming

Hydroponic farming is a type of horticulture which grows plants in nutrient-rich water instead of soil in an artificially controlled environment. It uses different materials like vermiculite, perlite, peat moss, coconut fibre, and rockwool to provide support to the roots of the plant. In hydroponics the plants roots are directly immersed in the nutrient solution and have access to oxygen. The nutrient solution would contain nutrients essential for the growth of plants like nitrogen, phosphorus, and potassium. Oxygen supply is maintained through oxygen pumps which keeps the water oxygenated.

2.4 Types of hydroponic systems

There are different types of hydroponic farming namely:

- Wick System
- Water Culture
- Ebb and Flow
- Drip
- N.F.T. (Nutrient Film Technology)

2.4.1 Wick System

The wick system is the simplest and the most basic hydroponic technique. It is the only hydroponic system that does not use electricity. In this technique the plants are placed in such a manner that they get supply of essential nutrients and water through a wick made of soft fabric like cotton and nylon placed directly into an absorbent substance like perlite or vermiculite. One end of the wick is connected to the plant and second end is suspended into the reservoir of nutrient solution. It follows the oil lamp technique wherein the wick only absorbs once the upper end supply is used up by the plant. This system is cheap to install and maintain. However, it cannot be used for larger plants and is best used for small herb plants. The larger plants need more nutrients for which the wicks don't have capacity. Another drawback is that it is difficult to control the flow of nutrients and may sometimes cause over dampness and lead to root rot.

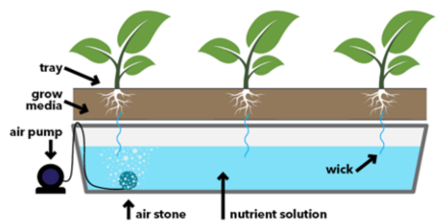

Figure 2: Wick System

2.4.2 Water Culture

This system is the advanced version of the wick system and yet simple. In this system the plant roots are directly placed into the nutrient solution and there is no connecting wick. So, the plant directly absorbs what it needs. The oxygen supply to the plant is controlled by a diffuser or air stone. In the absence of soil, the plants are kept upright and secure through net pots or floating raft like structures. This system can be used to grow a wider variety of plants and without major investment. The only drawback is that since the roots are directly suspended in a liquid all the time, there might be frequent root rot unless proper hygiene is maintained.

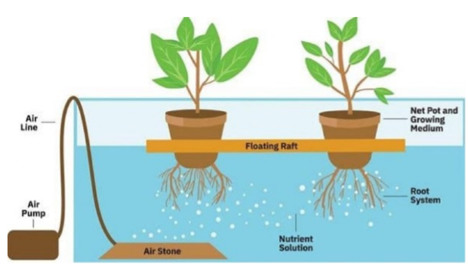

Figure 3: Water Culture

2.4.3 Ebb and Flow (Flood and Drain)

This system is more advanced than the above two. In this system the plant is not directly suspended into the nutrient solution but grown in a spacious grow bed that's packed with materials like rockwool or perlite as a replacement for soil. Once planted, the plant bed is supplied with the nutrient-rich solution as per the specific requirement of the plant and this flow is controlled by a pump. Most farmers have timers installed to be more meticulous. In case of an overflow the liquid water is sucked back by the pump. This system can accommodate a larger variety of plants and there is lesser chance of root rot as compared to the other two systems mentioned above. The farmers must ensure that the pump is calibrated and works well.

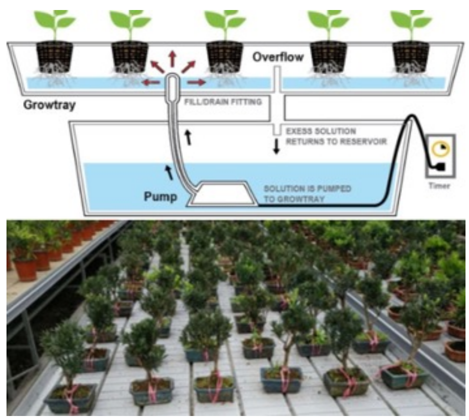

Figure 4: Ebb and Flow System

2.4.4 Drip Systems

This is fast becoming the most popular technique. It uses the traditional water efficient irrigating technique called the Drip system and applies it to hydroponics. In this system the plant is grown in a soil replacement material to hold the plant upright and the nutrient solution is delivered to the plant roots using drip irrigation. This technique ensures that the flow of nutrients is steady and efficient and there is no overflow. Plants are categorized in different containers that are regulated individually. A hydroponic drip system supplies moisture and nutrients based on the plant type and its specific requirements. The drip emitters may be calibrated to ensure greater efficiency or can be physically controlled. There are two types of Drip System Hydroponics: • Recovery system in which the drip supplies the nutrients, and the access is circulated back and reused. While this system is economical, it might need to be checked frequently as sometimes the pH gets disturbed as plants may absorb nutrients at different rates. • Non-Recovery systems are generally more efficient and calibrated to ensure there is no oversupply and in case there is an overt supply the extra is drained out of the system and not brought back in circulation.

This technique allows the producer to grow a larger variety of plants and is the most efficient while still being economical.

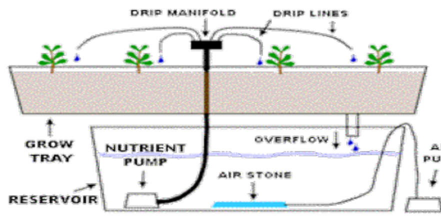

Figure 5: Drip System

2.4.5 N.F.T. (Nutrient Film Technology)

The system in terms of plantation is quite like the drip technique, except instead of drips they have sloped channels and even the plants are planted on a slope type raft or master container and suspended over the nutrient solution which is placed into a large reservoir. From here, the solution is pumped into sloped channels allowing the nutrients to flow down the slope and over the roots of each plant to provide nutrients supply. The excess is drained out.

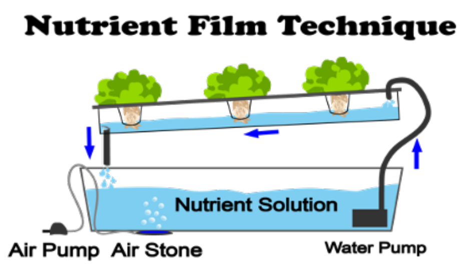

Figure 6: Nutrient Film Technology

2.5 Aeroponic Systems

In this system the plants are suspended in the air (as shown in diagram). Mist nozzles are positioned below to spray the nutrient solution onto the roots of each plant. The excess solution falls back into the reservoir and is drained with the excess falling down into the reservoir below. As the plants in this system are suspended in air, they get sufficient oxygen supply. The only drawback is that they are expensive systems to install.

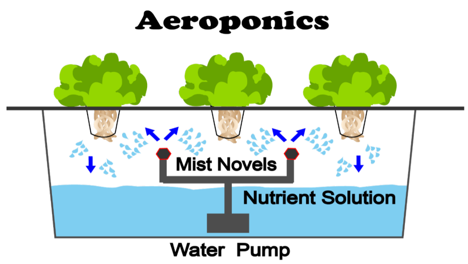

Figure 7: Aeroponic System

2.6 Aquaponics

Aquaponics is a hydroponic technique that mimics a natural ecosystem. It uses nutrient-rich waste produced from fish manure, algae and fish feed in fishponds that are normally thought of as contaminants. These so-called contaminants are nutritious for the plants. In return, the plants act as a biofilter and purify the wastewater, which is recycled and released into the attached fishponds. Thus, this can combine farming of plants with fish farming.

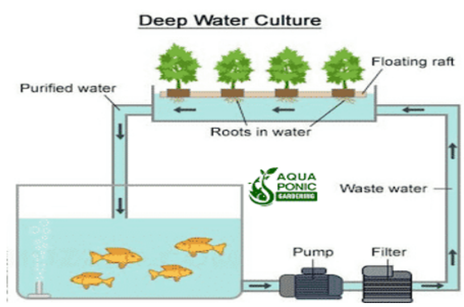

Figure 8: Aquaponic System

2.7 Hydroponics vs Conventional farming – case in favour of the latter

While traditional farming still forms the mainstay of farming across the world, hydroponics is gradually becoming popular. Traditional farming practices need land, fertile soil, water and sunlight as the basics and the shortage and gradual depletion of these natural resources is making traditional farming less productive progressively. Hydroponics does not need soil and land and can be undertaken anywhere in an artificially controlled environment. This allows even urban communities to take it up and reduce the pressure of food production on traditional farmers. It has the following advantages over traditional farming:

- 68% of the world population projected to live in urban areas by 2050, according to a UN report [oESA18]. Space constraints in urban areas does not allow traditional farming and so the pressure of producing food is transferred to rural population which is not being able to meet the increasing food demand. Hydroponic needs less space as compared to traditional farming methods and hence is more suitable to our world. This method allows urban communities to become self-reliant in terms of their food supply and reduces the pressure on our land and other natural resources.

• Traditional farming relies on natural resources. In traditional farming the plants spread their roots to locate water and nutrients, or they are fed mostly inorganic fertilizers which harm the soil. In hydroponic farming all nutrient supply is meticulously organized and so the roots need not occupy more than the basic space and so the yield and the number of plants grown per feet area is much denser and higher making the yield much higher.

• Hydroponic systems save water as they are operated in a controlled environment and brought back in circulation, whereas in traditional farming water is wasted due to evaporation and absorption by the surrounding soil. 2.3 billion people live in water-stressed countries, of which 733 million live in high and critically water-stressed countries [UW21]. Since the world could face acute water shortage, a mechanism that helps save this precious natural resource should be given its rightful priority.

• Traditional farming requires wide scale usage of pesticides and other chemicals to protect the crop. These in turn are very harmful for the soil and are causing huge environmental and health damage. Hydroponic systems use less chemicals as farming happens in an indoor closed environment where pests and weeds do not threaten the yield. The crop thus is more environmentally friendly and also does not have an adverse impact on our ecosystem and human health.

• The farming output is higher in hydroponic farming in comparison to traditional farming methods. The reason is that plants are given specific amounts of nutrients suited to the plant type and there is no stress from the natural environment. Since all the growing conditions are controlled, most adversity is removed, and plants get what they want and in the right quantity and at the right time.

• Traditional farming is seasonal whereas hydroponic farming is not dependent on weather and climatic conditions and can be done year-round as per choice and the growing conditions are artificially controlled. Moreover, regions with harsh climate that typically dependent on imports can now become self-reliant in terms of food supplies.

• The plants in hydroponic farming are not infected by any pests and are cleaner and hence save the pain of being cleaned and washed for human consumption and are a lot healthier and organic.

• The only downside of hydroponic farming are the installation and maintenance costs. The main expense comes from its usage of electricity for its fluorescent lighting. This extra cost can be avoided by using LED lights and thick insulation on buildings that house the hydroponics systems and by using wind and solar energies to run these vertical farms.

2.8 Singapore – a hydroponic success case study for the world

Spread across 710 square km and inhabited by 5 million people, Singapore is one of the world's most densely populated cities. Since most of its land is covered by the urban sprawl, Singapore does not have local food production for its people and has been reliant on food imports to feed its population. This makes living in Singapore very expensive.

Singapore became one of the first countries to adopt hydroponic vertical faming on a large scale with government and private collaboration. Entrepreneur Jack Ng, with the help of Agri-Food and Veterinary Authority (AVA), set up one of the world's first commercial vertical farms and set the pace for others. "It is the first low carbon hydraulic water-driven vertical system in the world to grow tropical-vegetables vertically in the tropics, which gives significant yield and uses less water, energy and natural resources, to achieve a sustainable green high-tech farm" declared Jack Ng, Managing Director of Sky Greens [Kri14]. He used his engineering skills to devise a system that controlled the installation and operational costs using protected environment of PVC roofing and netted walls to allow crop growth under natural sunlight all year round to keep the operational costs at the bare minimun. The company has claimed a much higher yield than traditional farming techniques and grows safe and organic produce which is now grown locally.

His first plant, spread over 60 square feet, was set up not far from the central business district and was a huge success. He has a total of 120 such towers as of today with plans for 300 more in the immediate future targeting to produce two tons of vegetables per day, which in conventional farming would have needed huge tracks of land. By setting up a plant within the city limits he is able to sell the produce more easily as he has a market readily available. The locals prefer the fresh vegetables produced and he has happy consumers. He does not have to worry about storage and transportation and thus is able to run a streamlined operation setting an example for other urban centres from across the world. According to the Singaporean government – "This will not only reduce the "food miles" but also mitigate supply shortages and hoarding. As one government official puts it, "We cannot depend totally on imports. We are a land scarce country and therefore need to be able to maximise use of our land in the area of food production. Local production acts as a buffer against severe disruptions in food supply." [Kri14]. COVID lockdowns also tested the utility of the project when supply lines were severely disrupted making local produce a precious commodity.

3 Conclusion

As the world stares at an environmental crisis and unprecedented stress on its natural resources, an outside of the box solution is essential to feed the ever-increasing population without further aggravating the environmental degradation. Hydroponics gives hope to various regions, each with their unique problems. There are countries with harsh climatic conditions that have been dependent on others for food supplies for generations. Now they have hope. The UAE is another example of a region otherwise categorized as a desert which has used this technique to increase its green cover and also become self-reliant to a certain degree in terms of fresh food supplies. Then there are countries like India which are very densely populated causing distress on its natural resources like land and water. A country like India needs these modern solutions or it will soon find itself in a future of hunger and thirst. Hydroponic farming helps save two of the world's most important resources, land and water, and hence cannot be ignored by nations. Hydroponic crops need 50% to 90% less water than traditional farming and hence can become an especially important means of conservation without any collateral damage. In fact, it only has collateral benefits as elaborated above. As Singapore has shown, it can help big cities with very scarce and expensive land and water resources become self-sufficient and reliant. Japan too has used this technique successfully. Many Japanese cities have put unused spaces (closed factories or shops, or buildings) to effective use by converting them into vertical farms.

It is apparent that countries like India with large populations and extremely stressed land resources cannot afford to ignore this system if it has to find a solution to its looming food and water demand.

Critics point towards the high installation and operational costs and its high energy consumption which is a point to be noted and worked upon. The hydroponic farms in Singapore have tried to get around this drawback by ensuring that the buildings are better ventilated and allow natural light to reduce the use of artificial light to cut down the energy consumption. Countries with adequate sunshine can follow this example and not totally depend on an artificially controlled environment. Some companies in countries with adequate sunshine are relying on solar lamps to reduce operational costs and make the farming more cost effective. The advantages of hydroponic farming clearly outweigh its drawbacks in terms of reducing stress on natural resources like land and water.

The world environmental crisis and global warming has compelled countries to take corrective action and here too hydroponic farming may come handy. Hydroponic farms in dense urban sprawls can help reduce pollution and balance the extreme waste heat generated in these cities. Moreover, hydroponic farms can put sewage water to good use and help in treating the water with no side effects. The Neknampur lake in India became a successful case study of how hydroponics can be used to clean urban water bodies choking with pollutants causing a great deal of harm to the environment. Called floating treatment wetlands (FTW), these artificially created islands use the hydroponics system to use plants to cleanse the water.

Hydroponics is a great tool for creating self-sustainable and reliant urban communities. Even poor and lower middle-class families can use this technique to grow vegetables on their own urban dwellings. The extra cost is compensated by lower food bills, and they get to eat healthier diets. It's a win-win situation. Sociologists feel that communities can get together and make a collective effort which is mutually beneficial but also gives them a joint sense of purpose making them bond better.

Cities are major contributors to climate change. According to UN Habitat, “cities consume 78 per cent of the world’s energy and produce more than 60 per cent of greenhouse gas emissions. Yet, they account for less than 2 per cent of the Earth’s surface” [Hab11]. Furthermore, according to the Intergovernmental Panel on Climate Change (IPCC) report, limiting global warming to 1.5 degrees Celsius would “require rapid and far-reaching transitions in uses of energy, land, urban and infrastructure (including transport and buildings), and industrial systems” [MDW18]. Another UN report forewarns that another 2.5 billion people will reside in urban areas by 2050; nearly 90 per cent of them in cities in Asia and Africa [oESA18]. Hydroponics seems to be one of the better solutions as it helps absorb the excessive carbon dioxide in the air and releases much needed oxygen while putting no pressure on the limited land resource. Latest developments in alternative sources of energy have thankfully warded off the criticism that hydroponics is very energy consuming and expensive. Latest hydroponic efforts are now powered by wind or solar power. As mentioned earlier reducing the transportation time lines by producing food locally, we save on transportation which would use fuel thus helping conserve the precious commodity that is also the main cause of carbon emission.

Hydroponics with its promise of increased yield using sustainable measures that are safe for the environment will go a long way in helping the world preserve its natural resources. Decreased pressure on traditional farming will give breathing space to the world’s land resources which have been over cropped, and stand worn out and depleted. We could reduce agricultural tracks and rebuild our forest cover and natural landscape and restore our lost ecosystem balance. Frankly we don’t have too much of a choice in the matter. If we continue to use conventional farming’s inorganic methods, we will destroy our environment. Use of GMOs, fertilizers and pesticides by most countries to increase produce has caused alarming damage to our environment and impacted our biodiversity adversely. While the GMOs have interfered with the natural genetic makeup of living organisms linked together in a delicate ecosystem and caused abnormalities, use of pesticides and fertilizers have cause irreparable damage to our soil cover. We have to take our chances and welcome the most sustainable agricultural practice to better our odds in saving our world.

References

[AM22] Giovanni Battists Ponzetto Joseph Wang Nicholas Glinsman Patrick Perret-Green Tracy Shucart Velina Tchakavora Alberto Marko, Alessandro Ponzetto. Asia pacific geopolitics. 2022.

[DC15] Peter Horton Mark Sinclair Duncan Cameron, Colin Osborne. A sustainable model for intensive agriculture. *Graham Centre for Sustainable Futures*, 2015.

[Des11] Dickson Despommier. The vertical farm: controlled environment agriculture carried out in tall buildings would create greater food safety and security for large urban populations. *Journal of Consumer Protection and Food Safety*, 2011.

[EI18] The Energy and Resources Institute. Economics of desertification, land degradation and drought in india. 2018.

[FA21] ECA FAO and AUC. Africa – regional overview of food security and nutrition 2021: Statistics and trends. *Journal of Consumer Protection and Food Safety*, 2021.

[FAO20] FAO. Land use in agriculture by the numbers. 2020.

[Hab11] United Nations Habitat. New cities and climate change: Global report on human settlements 2011. 2011.

[Hau17] Eri Hauashi. Japan special report: Plant factories with artificial light (pfal). 2017.

[IU15] ELD Initiative and UNEP. The economics of land degradation in africa: Benefits of action outweigh the costs. 2015.

[Koz13] Toyoki Kozai. Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. *Proceedings of the Japan Academy, Series B*, 89(10):447–461, 2013.

[Kri14] Ravindra Krishnamurthy. Vertical farming: Singapore's solution to feed the local urban population. *Premaculture Research Institute*, 2014.

[MDW18] P. Zhai H.-O. Pörtner D. Roberts J. Skea P.R. Shukla A. Pirani W. Moufouma-Okia C. Péan R. Pidcock S. Connors J.B.R. Matthews Y. Chen X. Zhou M.I. Gomis E. Lonnoy T. Maycock M. Tignor Masson-Delmotte, V. and T. Waterfield. Ipcc,2018: Summary for policymakers. in: Global warming of 1.5°c. an ipcc special report on the impacts of global warming of 1.5°c above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. *Cambridge University Press, pp. 3-24*, 2018.

[MH22] Theresa Nogeire-McRae Scott Beck Stacy Shutts Ryan Murphy Mitch Hunter, Ann Sorensen. Farms under threat 2040: Choosing an abundant future. *American Farmland Trust*, 2022.

[oA21] U.S Department of Agriculture. Vertical farming for the future. 2021.

[oESA18] United Nations Department of Economic and Population Division Social Affairs. World urbanization prospects: The 2018 revision (key facts). 2018.

[oESA19] United Nations Department of Economic and Population Division Social Affairs. World urbanization prospects 2018: Highlights. 2019.

[oESA22] United Nations Department of Economic and Population Division Social Affairs. World population prospects 2022: Summary of results. 2022.

[SM21] Nora Berrahmouni Stephanie Mansourian. Review of forest and landscape restoration in africa. *FAO and AUDA-NEPAD*, 2021.

[TA17] Sven Peets-Thomas Joseph Norton Tobi Adeyemi, Ivan Grove. Advanced monitoring and management systems for improving sustainability in precision irrigation. *Sustainability*, 2017.

[UW21] UN-Water. Summary progress update 2021 – sdg 6 – water and sanitation for all. version: July 2021. 2021.

[Xin03] Li Xin. Pressure of water shortage on agriculture in arid region of china. *Chinese Geographical Science,13(2), 124-129*, 2003.