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Water-Energy-Food Nexus (WEFN), Sustainable Agriculture and Technology

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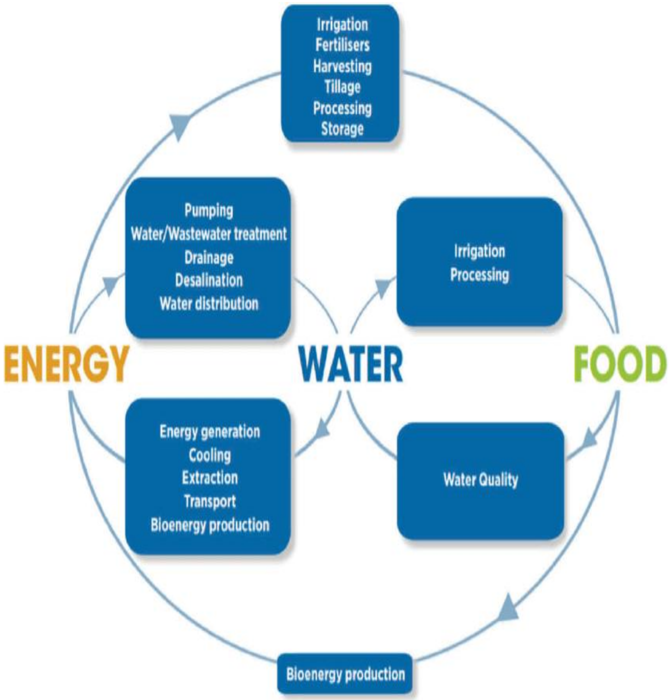
Hydroponics and aquaponics, as methods of soil-less farming, have gained significant popularity as a means to reduce reliance on arable land and produce crops closer to where they will be consumed. Indoor farming in controlled environments shields plants from adverse weather, pests, and insects, preventing nutrient loss and drastically reducing water usage compared to traditional agriculture. However, artificial lighting and climate control require energy input, which can be effectively supplied through solar rooftop systems, transforming the plant production into an off-grid operation. Despite these advantages, these methods are capital-intensive and demand specialized technical expertise. There is a lack of comprehensive data on the environmental impact of these systems, particularly in India, making scalability a challenge. In Uttarakhand, with its diverse agro-climatic conditions, agriculture remains a primary occupation, particularly subsistence farming on terraced fields in the hills. Yet, commercial agriculture is predominantly practiced in the plains, with horticulture representing only a small portion of land use. This paper explores the need for integrated research into sustainable farming technologies and the Water-Energy-Food Nexus (WEFN) approach to address the challenges of food security and resource management, especially in regions like Uttarakhand.

Uttarakhand diverse agro-climatic zones, ranging from hills to plains, sustain a population where 75-85% depends on agriculture. While commercial agriculture is more common in the plains, traditional subsistence farming remains widespread in the hilly regions. Irrigation driven by tube wells has significantly boosted productivity in India over the last few decades, especially through the use of groundwater. As global population growth is projected to rise by 2.3 billion people between 2009 and 2050, the demand for food continues to increase. The search for resilient and sustainable food production methods, especially in urban-adjacent areas, becomes ever more pressing. Greenhouse farming and hydroponic systems offer promising solutions, allowing crops to be grown indoors in controlled environments. These methods conserve water and eliminate nutrient leakage, using less water compared to traditional farming. However, despite their potential, there is limited data on their environmental footprint, particularly in the Indian context. The Water-Energy-Food Nexus (WEFN) provides a systematic framework to understand and manage the interconnections between these critical resources, enhancing food security and promoting sustainable agricultural practices.

Water-Energy-Food Nexus

WEFN through Solar Greenhouse-Based Hydroponic Solutions with Android Mobile Application for Rural Farmers and Urban Users' is an R&D initiative funded by the Department of Science and Technology (DST) under its Water Energy Food Nexus call. The study aims to empirically link the WEFN approach with data collected from the Dehradun Valley in Uttarakhand. Key objectives include conducting crop inventories, assessing energy and water



consumption, evaluating water and electricity pricing policies, and determining optimal high-value crops for resource-efficient farming. This is supplemented by farmer skill development through stakeholder meetings and field surveys. A crucial part of the study involves the creation of a Water-Energy-Food Nexus Index (WEFNI), which helps optimize crop choices for hydroponic farming systems powered by solar energy. The establishment of a SMART Solar-based Hydroponic System at UCOST features automated monitoring and control of environmental parameters, ensuring optimal conditions for crop growth. Additionally, an Android mobile application has been developed to link farmers with market logistics, enhancing access to markets for hydroponic and other crops.

Role of Water and Energy in Hydroponics

Hydroponics is rapidly becoming a leading sector in agriculture and has the potential to dominate future food production. As the global population rises and arable land decreases due to poor land management, soil degradation, and erosion—especially in hilly regions—innovative technologies like hydroponics and aeroponics will play a crucial role in creating new avenues for crop production. Early adopters of hydroponic systems provide insight into its future potential (Singh, S. 2016). For instance, in Tokyo, where land is scarce and valuable, hydroponic rice is grown in underground vaults without soil, allowing for four annual harvests instead of the traditional single harvest. Similarly, in Israel's dry and arid climate, companies like Organitech are growing large quantities of crops such as berries and citrus fruits using hydroponic systems inside shipping containers, achieving yields up to 1,000 times greater than conventional farming on the same land area. These systems are fully automated, using robotics in a process similar to assembly lines in manufacturing plants, and the containers are easily transported across the country. Hydroponics has drawn attention for its potential to address food security in water-scarce regions, such as parts of Africa and Asia. While the initial setup costs of hydroponic systems remain a significant barrier, technological advancements are expected to drive down costs over time, making it a viable solution for feeding millions in regions with limited water resources.

Reducing the Energy Footprint of Hydroponics: Solar-Powered Hydroponics

Hydroponic systems require energy to power lighting, water treatment, and other essential equipment. One critical challenge for hydroponic farming is that any power outage can halt the system, leading to crop loss within hours. Therefore, large-scale systems must always have backup power sources to mitigate this risk. Initial investments in equipment—such as containers, lights, pumps, timers, growing media, and nutrients—can be substantial, but ongoing operational costs are mainly limited to nutrients and electricity. However, for large-scale commercial growers, the high upfront expenses and uncertain return on investment (ROI) remain challenges. Hydroponic farms outperform traditional greenhouse farming in terms of productivity, especially when powered by renewable energy sources like solar or wind. When fossil fuels are used to power the system, the environmental benefits diminish. However, hydroponics becomes the most environmentally efficient form of agriculture when powered by carbon-neutral energy sources. Furthermore, hydroponics enables food production without the need for large areas of agricultural land, which is particularly beneficial in urban areas where land is limited. Our study aims to optimize hydroponic systems by integrating solar energy to power key components such as temperature control, water pumps, and air pumps. This system will be based on Peripheral Interface Controller (PIC) technology and will use solar panels, which are one of the cleanest ways to generate electricity. Given India’s geographic advantages for solar power, this approach will not only reduce the environmental impact of hydroponics but also offer a viable solution within the Water-Energy-Food Nexus (WEF Nexus) framework. By combining electrical, electronic, and agricultural technologies into a single sustainable system, solar-powered hydroponics could prove to be a scalable and eco-friendly solution for future food production.

Benefits of Hydroponics Farming

- **No soils needed:** In a sense, you can grow crops in places where the land is limited, doesn't exist, or is heavily contaminated or degraded. Hydroponics has been considered as the farming of the future to grow foods for astronauts in the space (where there is no soil) by NASA.

- **Make better use of space and location:** As all that plant's needs are provided and maintained in a controlled environment/system, it can be grown indoors and vertically multiplying produce per square feet to multifold.
- Climate control: Like in greenhouses, hydroponic growers can have total control over the climate - temperature, humidity, light intensification, the composition of the air. In this sense, you can grow foods all year round regardless of the season. Farmers can produce foods at the appropriate time to maximize their business profits.
- **Hydroponics is water-saving:** Plants grown hydroponically can use only 10-25 per cent of water compared to field-grown ones. In this method, water is re-circulated. Plants will take up the necessary water, while run-off ones will be captured and return to the system. Water loss only occurs in two forms - evaporation and leaks from the system (but an efficient hydroponic setup will minimize or don't have any leaks).
- **Effective use of nutrients:** In Hydroponics, one has a 100% control of the nutrients that plants need. Before planting, growers can check what plants require and the specific amounts of nutrients needed at particular stages and mix them with water accordingly. Nutrients are conserved in the tank, so there are no losses or changes of nutrients like they are in the soil.
- **pH control of the solution:** All of the minerals are contained in the water. That means one can measure and adjust the pH levels of your water mixture much more easily compared to the soils. That ensures the optimal nutrients uptake for plants.
- **Better growth rate:** Hydroponically plants grow faster than in soil if plants are placed in ideal conditions, while nutrients are provided at the sufficient amounts, and come into direct contacts with the root systems. Thereby, plants no longer waste valuable energy searching for diluted nutrients in the soil. Instead, they shift all of their focus on growing and producing fruits.
- **Amenable to speed breeding technologies:** Hydroponics is compatible with speed breeding approaches (Hickey et al. 2019) wherein light conditions (photoperiod and quality) may be controlled to accelerate the life cycle of crops/ plants/ vegetables thereby reducing the duration of cropping cycle.
- **No weeds:** Weeds are mostly associated with the soil. So by eliminating soils weeds is indirectly controlled.
- **Fewer pests & diseases:** And like weeds, getting rids of soils helps make your plants less vulnerable to soil-borne pests like birds, gophers, groundhogs; and diseases like Fusarium, Pythium, and Rhizoctonia species. Also when growing indoors in a closed system, the gardeners can easily take controls of most surrounding variables.
- **Less use of insecticide, and herbicides:** Since you using no soils and while the weeds, pests, and plant diseases are heavily reduced, there are

fewer chemicals used. This helps one grow cleaner and healthier foods. The cut of insecticide and herbicides is a strong point of Hydroponics when the criteria for modern life and food safety are more and more placed on top.

- **Labour and time savers:** Besides spending fewer works on tilling, watering, cultivating, and fumigating weeds and pests, when agriculture is planned to be more technology-based

- human intervention can be minimized to a very large extent.

Conclusion

This solar-based hydroponic model, developed in the Doon Valley, can be replicated in other parts of Uttarakhand and the wider Himalayan region. Its potential to boost local farmers' incomes by enabling the production of multiple high-value crops annually, while minimizing water and energy use, aligns with broader goals of sustainable agriculture and rural development. By integrating renewable energy sources, advanced monitoring systems, and market connectivity, this initiative supports the socio-economic development of mountain communities. It aligns with the goals of the National Mission for Himalayan Studies (NMHS) and the Water Technology Initiative (WTI) under the Government of India’s Department of Science and Technology.