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Water – Efficient Technologies for Sustainable Vegetable Cultivation

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Abstract

Water is the single most limiting input in vegetable production and increasing competition among agricultural, domestic and industrial users has made efficient water use an urgent priority for horticulturists and policy makers alike. Vegetables are generally shallow-rooted, fast-growing and highly sensitive to even short periods of water stress, which makes them particularly vulnerable to yield and quality losses under water scarcity, but also highly responsive to improved water management. This review synthesises current knowledge on water-saving technologies applicable to vegetable production, including drip and subsurface drip irrigation, plastic and organic mulching, deficit and regulated deficit irrigation (RDI), partial root-zone drying (PRZD), fertigation, protected cultivation, rainwater harvesting and recycled-water use, and sensor- and IoT-based precision irrigation scheduling. Evidence from field studies indicates that drip irrigation combined with mulching can reduce irrigation water use by 20–50% relative to conventional surface irrigation while maintaining or increasing marketable yield and that regulated deficit irrigation can further improve water productivity when applied during growth stages that are less sensitive to water stress. The review also discusses the practical constraints to adoption, including capital cost, technical skill requirements and site-specific calibration needs and identifies future research priorities such as integration of low-cost soil moisture sensors, remote sensing and machine-learning-based irrigation scheduling for smallholder vegetable systems. The overall conclusion is that no single technology is universally optimal; rather, the greatest water savings and economic returns are achieved when complementary technologies are combined and tailored to local soil, crop and climatic conditions.

Keywords: water-use efficiency; drip irrigation; mulching; deficit irrigation; vegetable crops; precision irrigation.

1. Introduction

Agriculture consumes nearly 70% of global freshwater resources, with irrigated vegetable production being one of the most water intensive agricultural sectors because of the high evapotranspirational demand and shallow root systems of most vegetable crops (Allen *et al.,* 1998). Increasing water scarcity caused by climate change, groundwater depletion and rising competition for water has made efficient irrigation management essential (Fereres and Soriano, 2007). Conventional surface irrigation is often inefficient, whereas modern water-saving technologies such as drip irrigation, deficit irrigation, subsurface drip irrigation, mulching, protected cultivation, soil moisture sensors, remote sensing, and automated fertigation significantly improve water-use efficiency while maintaining or enhancing crop yield and quality. Since vegetable crops are highly sensitive to water stress during critical growth stages such as flowering and fruit development (Doorenbos and Kassam, 1979), these technologies help optimize water application and reduce non-productive losses. Therefore, the adoption of water-saving technologies is vital for achieving sustainable and resource-efficient vegetable production.

2. Water-Saving Technologies in Vegetable Production

2.1 Drip and Subsurface Drip Irrigation

Drip irrigation is one of the most efficient water saving technologies in vegetable production, as it delivers water directly to the root zone, thereby reducing evaporation, runoff and deep percolation losses. In broccoli, gravity-fed drip irrigation at 80% ETc saved 21–53% of irrigation water while maintaining or increasing curd yield and improving irrigation water productivity by 46–70% compared to surface irrigation (Patra *et al.,* 2022). Likewise, subsurface drip irrigation (SSDI) further enhances water use efficiency by minimizing surface evaporation. A global meta-analysis reported that SSDI increased crop yield, irrigation water productivity and overall water productivity by 5.4%, 6.8% and 4.0%, respectively, over conventional irrigation, with the greatest benefits observed at emitter spacing below 25 cm and burial depths below 10 cm (Wang et al., 2022). Similar benefits also been reported in cotton, where alternate partial root-zone drip irrigation reduced irrigation water use by up to 30% without significantly affecting yield (Du et al., 2008).

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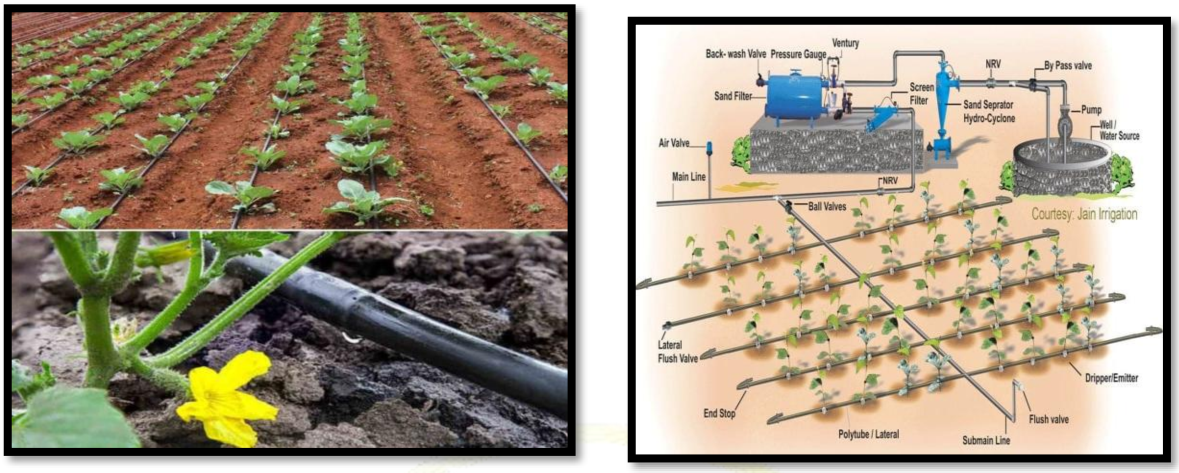

Fig. 1. Drip irrigation system in vegetable crops and layout of subsurface drip irrigation

2.2 Mulching (Plastic and Organic)

Mulching suppresses soil evaporation, moderates soil temperature and controls weeds that would otherwise compete for soil moisture. Black polyethylene mulch combined with drip irrigation has been shown to increase curd yield of broccoli by nearly 17% and crop water productivity by 15% relative to unmulched plots, with paddy-straw mulch giving a smaller but still significant benefit (Patra *et al.,* 2022). Organic mulches such as straw, crop residues or plant-based materials additionally add organic matter to the soil and are often preferred where cost or environmental concerns limit the use of plastic film. The combination of drip irrigation with plastic mulching is now regarded as one of the most reliable 'climate-smart' packages for water-scarce vegetable production, since the two technologies address complementary sources of water loss – the drip system reduces the volume applied, while the mulch reduces the volume lost to evaporation once applied (Kashyap *et al*., 2009).

Fig.2. Plastic and organic mulch in vegetables

2.3 Deficit Irrigation and Regulated Deficit Irrigation (RDI)

Deficit irrigation deliberately supplies less water than full crop evapotranspiration requirement, accepting a small, planned yield reduction in exchange for substantial water savings. Regulated deficit irrigation refines this concept by timing the imposed stress to growth stages that are least sensitive to water deficit, thereby minimising the yield penalty (Yang *et al.,* 2022). The crop yield response factor (Ky), quantifies the proportional yield loss expected per unit of relative evapotranspiration deficit and remains the standard tool for designing deficit-irrigation schedules; crops with Ky values below 1.0 tolerate water stress with a proportionally smaller yield reduction and are therefore good candidates for RDI. In broccoli, moderate deficit irrigation at 80% ETc achieved yield and profitability statistically comparable to full irrigation while using appreciably less water, whereas a more severe deficit of 60% ETc caused a measurable yield decline, illustrating the trade-off that RDI scheduling must manage (Patra *et al.,* 2022).

2.4 Partial Root-Zone Drying (PRD)

Partial root-zone drying alternates irrigation between two sides of the root system, allowing part of the roots to experience mild drying while the other part remains moist. The drying roots generate chemical signals (notably abscisic acid) that reduce stomatal conductance and transpiration without a proportional reduction in photosynthesis, so that water use efficiency improves even though total water applied is reduced (Kang and Zhang, 2004).

2.5 Fertigation and Precision Nutrient-Water Management

Fertigation, the transfer of soluble fertilisers through drip or micro-irrigation systems, allows water and nutrients to be supplied together in small, frequent doses matched to real-time crop demand. This synchronisation reduces nutrient leaching below the root zone, a common problem under conventional irrigation and fertilisation and studies in drip-irrigated tomato have shown that scheduling irrigation and nitrogen fertigation according to real-time soil moisture and crop needs markedly improves both water productivity and nitrogen-use efficiency compared with fixed calendar-based scheduling (Zotarelli et al., 2009). Because vegetable crops are typically fertilised h eavily to sustain rapid growth, fertigation is now considered an integral part of water-saving technology packages rather than a separate practice.

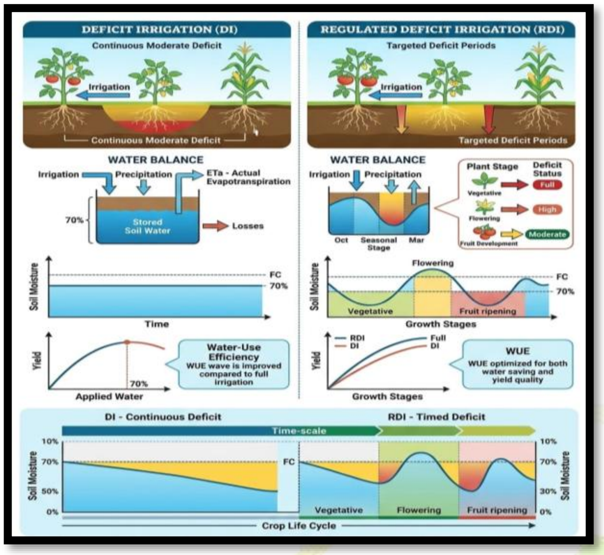

Fig. 3. Deficit Irrigation and Regulated Deficit Irrigation (RDI)

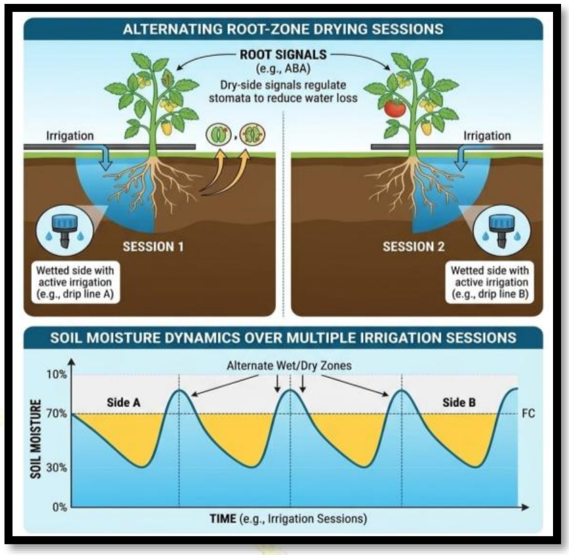

Fig. 4. Partial Root-Zone Drying

2.6 Protected Cultivation and Shade-Net Systems

Greenhouses, low tunnels and shade-net structures reduce crop water demand by moderating temperature, wind speed and vapour pressure deficit around the crop canopy, thereby lowering reference evapotranspiration relative to open-field conditions. When combined with drip irrigation, protected cultivation structures allow highly precise control over the microclimate and water supply, which is particularly valuable for high-value vegetables such as capsicum, cucumber and leafy greens grown in arid or semi-arid regions. Photo-selective shade nets additionally reduce direct solar radiation load on the crop, lowering both crop water requirement and pest pressure, making them a useful complementary water-saving tool in hot climates.

2.7 Rainwater Harvesting and Use of Treated Wastewater

In-situ and ex-situ rainwater harvesting structures, such as farm ponds, check dams and contour trenches, capture surplus monsoon or seasonal runoff for supplemental irrigation during dry spells, reducing dependence on groundwater and enabling continuity of vegetable cultivation in rain-fed areas. Similarly, treated municipal or agricultural wastewater, when used cautiously with attention to salinity and pathogen risk, provides an additional non-conventional water source; partial root-zone drying combined with recycled water has been evaluated as a way of maintaining tomato yield while easing pressure on freshwater resources in water-scarce regions, although careful monitoring of soil salinity and heavy-metal accumulation is required for sustainable long-term use.

2.8 Sensor-Based and Precision Irrigation Scheduling

Advances in low-cost soil moisture sensors, tensiometers and wireless sensor networks now allow irrigation to be triggered automatically when soil water content falls below a defined threshold, rather than on a fixed calendar basis. A real-time wireless sensor array deployed in cotton fields demonstrated that automated, sensor-triggered irrigation scheduling could reduce water applied while maintaining yield relative to conventional scheduling, a principle equally applicable to vegetable systems (Vellidis *et al.,* 2008). Complementary tools such as canopy temperature sensing, remote sensing of crop water stress index and simple plant-based indicators (leaf water potential, stomatal conductance) provide additional, non-invasive means of scheduling irrigation with high temporal precision (Jones, 2004). The integration of these sensors with Internet-of-Things (IoT) connectivity and simple decision-support software is an emerging area with strong potential for smallholder vegetable farms, since it removes much of the guesswork from irrigation timing.

3. Applications, Benefits, Constraints, Future Prospects and Conclusion

Water-saving technologies are most effective when used in combination rather than individually. Integrating drip irrigation with mulching, fertigation, and deficit irrigation has consistently resulted in greater water savings, higher water-use efficiency, and improved economic returns. In broccoli, drip irrigation at 80% ETc combined with black polyethylene mulch provided the highest benefit-cost ratio, while irrigation at 60% ETc with mulch achieved maximum water savings under severe water scarcity (Patra *et al.,* 2022). Similarly, stage-specific deficit irrigation in onion and alternate partial root-zone drip irrigation in crops such as tomato, pepper, and cotton have demonstrated considerable water savings without significant yield reduction (Doorenbos & Kassam, 1979; Du *et al*., 2008). Water conserved through efficient irrigation can also be used to expand the cultivated area, thereby increasing production without increasing total water use (Patra *et al*., 2022). Subsurface drip irrigation combined with mulching further enhances irrigation efficiency, particularly under arid conditions (Wang *et al.,* 2022). Moreover, modern tools such as soil moisture sensors, canopy temperature sensing, remote sensing, and IoT-based irrigation systems enable precise irrigation scheduling and improve water management (Jones, 2004).

The major benefits of these technologies include reduced irrigation water requirement, increased water productivity, improved crop yield and quality, reduced nutrient leaching, and lower weed and disease incidence (Fereres and Soriano, 2007). However, their adoption is often restricted by high installation costs, maintenance requirements, emitter clogging, limited technical knowledge, and inadequate crop-specific information for deficit irrigation scheduling. Plastic mulch also poses environmental concerns due to disposal issues, while sensor-based irrigation systems require improved affordability and farmer training.

Future research should focus on developing crop- and cultivar-specific water sensitivity data, affordable soil moisture sensors, remote-sensing technologies, biodegradable mulches, and integrated irrigation–fertigation systems to enhance water-use efficiency (Yang *et al.,* 2022; Jones, 2004; Vellidis *et al*., 2008). Further validation of subsurface drip irrigation and partial root-zone drying under diverse agro-climatic conditions is also essential (Wang *et al.,* 2022).

In conclusion, water-saving technologies such as drip and subsurface drip irrigation, deficit irrigation, partial root-zone drying, mulching, fertigation, and sensor-based irrigation scheduling can reduce irrigation water use by approximately 20–50% while maintaining or improving vegetable yield, quality, and profitability. Their combined application, tailored to local soil, crop, and climatic conditions, offers the most effective strategy for sustainable vegetable production under increasing water scarcity. Continued research, technological innovation, and stronger extension support are essential for promoting their large-scale adoption, particularly among smallholder farmers.

References

1. Allen, R.G., Pereira, L.S., Raes, D., & Smith, M. (1998). Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper No. 56. Food and Agriculture Organization of the United Nations, Rome.
2. Doorenbos, J., & Kassam, A.H. (1979). Yield Response to Water. FAO Irrigation and Drainage Paper No. 33. Food and Agriculture Organization of the United Nations, Rome.
3. Du, T., Kang, S., Zhang, J., & Li, F. (2008). Water use and yield responses of cotton to alternate partial root-zone drip irrigation in the arid area of north-west China. *Irrigation Science*, 26, 147–159.
4. Fereres, E., & Soriano, M.A. (2007). Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*, 58(2), 147–159.
5. Jones, H.G. (2004). Irrigation scheduling: advantages and pitfalls of plant-based methods. *Journal of Experimental Botany*, 55(407), 2427–2436.

6. Kang, S., & Zhang, J. (2004). Controlled alternate partial root-zone irrigation: its physiological consequences and impact on water use efficiency. *Journal of Experimental Botany*, 55(407), 2437–2446.

7. Kashyap, S., Phookan, D.B., Baruah, P., & Bhuyan, P. (2009). Effect of drip irrigation and polythene mulch on yield, quality, water use efficiency and economics of broccoli production. *Indian Journal of Horticulture*, 66(3), 323–325.

8. Patra, S.K., Poddar, R., Pramanik, S., Gaber, A., & Hossain, A. (2022). Crop and water productivity and profitability of broccoli (Brassica oleracea L. var. italica) under gravity drip irrigation with mulching condition in a humid sub-tropical climate. *PLOS ONE*, 17(3), e0265439.

9. Vellidis, G., Tucker, M., Perry, C., Kvien, C., & Bednarz, C. (2008). A real-time wireless smart sensor array for scheduling irrigation. *Computers and Electronics in Agriculture*, 61(1), 44–50.

10. Wang, H., Wang, N., Quan, H., Zhang, F., Fan, J., Feng, H., Cheng, M., Liao, Z., Wang, X., & Xiang, Y. (2022). Yield and water productivity of crops, vegetables and fruits under subsurface drip irrigation: A global meta-analysis. *Agricultural Water Management*, 269, 107645.

11. Yang, B., Fu, P., Lu, J., Ma, F., Sun, X., & Fang, Y. (2022). Regulated deficit irrigation: an effective way to solve the shortage of agricultural water for horticulture. *Stress Biology*, 2(1), 28.

12. Zotarelli, L., Dukes, M.D., Scholberg, J.M.S., Muñoz-Carpena, R., & Icerman, J. (2009). Tomato nitrogen accumulation and fertilizer use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. *Agricultural Water Management*, 96(8), 1247–1258.