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Review Article

Drip Irrigation and Deficit Irrigation for Vegetable Production in Semi-Arid Sub-Saharan Africa: Water Productivity, Yield, Quality, and Smallholder Adoption

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Abstract

Most vegetable production in semi-arid sub-Saharan Africa (SSA) is rain-fed or irrigated by inefficient furrow and bucket methods, leaving farmers vulnerable to dry spells, low yields, and seasonal price spikes (FAO, 2020; Burney et al., 2010). Drip irrigation, which delivers water slowly and directly to the root zone, and deficit irrigation, which deliberately applies less water than full crop demand, offer complementary strategies to raise water productivity, the kilograms of produce per cubic metre of water applied (Fereres and Soriano, 2007; Geerts and Raes, 2009). This article synthesises peer-reviewed evidence published between 2000 and 2025 on drip and deficit irrigation for tomato, onion, pepper, cabbage, and other vegetables in semi-arid SSA. It reviews irrigation methods, crop water requirements, scheduling, fertigation, and the effects of deficit irrigation on yield, quality, and water productivity. Evidence shows that drip irrigation can reduce water use by 18 to 46 percent while increasing vegetable yields by 9 percent to about two-fold compared with conventional tillage and furrow irrigation in trials in Ethiopia and Ghana (Assefa et al., 2022). For tomato, deficit irrigation at 70 percent of crop evapotranspiration (ETc) produced the highest water productivity, about 7.0 kg m-3, with a moderate yield reduction, while deficit irrigation at 50 to 70 percent ETc increased water productivity in wheat by 48 percent with only 16 percent yield loss and in tomato by 51 percent with 21 percent yield loss in a meta-analysis of Ethiopian studies (Gebrehiwot et al., 2021; Desta et al., 2023). The article proposes a practical, low-cost drip-plus-deficit system for smallholders, including gravity-fed kits, solar pumps, mulching, and simple scheduling, and it identifies priorities for financing, maintenance, water governance, and extension. The central argument is that the goal for semi-arid vegetables should not be maximum yield per hectare at any water cost, but maximum income and nutrition per unit of water, and that drip plus carefully timed deficit irrigation is the most reliable way to achieve it.

Keywords: drip irrigation; deficit irrigation; water productivity; tomato; onion; vegetables; semi-arid; sub-Saharan Africa

1. Introduction

Vegetables are essential for nutrition, income, and employment in SSA. Tomato, onion, pepper, cabbage, okra, and leafy vegetables provide vitamins, minerals, and cash in both rural and urban markets, and they are often grown by women and youth on small plots near water sources (FAO, 2020). Yet vegetable production is one of the most water-sensitive enterprises in agriculture. A week without water at flowering or fruiting can destroy a tomato crop, while a week of waterlogging can destroy an onion crop. In semi-arid areas, where rainfall is low, variable, and concentrated in a short season, reliable water is the difference between a profitable dry-season crop and no crop at all.

Irrigation in SSA remains underdeveloped. Only a small fraction of cultivated land is irrigated, and much of

that irrigation is by furrow, flood, or bucket, methods that lose large amounts of water to evaporation, runoff, and deep percolation (Burney et al., 2010; FAO, 2020). Smallholders who do irrigate often over-irrigate when water is available and under-irrigate when it is scarce, with little scheduling based on crop demand, soil moisture, or weather. The result is low water productivity: a lot of water produces a little vegetable.

Two ideas, taken together, can change this. Drip irrigation delivers water directly to the root zone through emitters, reducing evaporation and runoff and allowing precise control of amount and timing (Fereres and Soriano, 2007). Deficit irrigation deliberately applies less water than the crop would use if fully irrigated, accepting a small yield reduction in exchange for a large water saving that can be used to irrigate a larger area or to save pumping cost (Geerts and Raes, 2009). This article asks three questions. First, how does drip irrigation affect water use, yield, and quality for vegetables in semi-arid SSA? Second, when does deficit irrigation increase water productivity without causing unacceptable yield or quality loss? Third, what low-cost, maintainable system can smallholders actually adopt, and what support does it require?

2. Water, Crops and the Concept of Water Productivity

Crop water requirement is expressed as crop evapotranspiration, ETc, the product of reference evapotranspiration, ETo, and a crop coefficient, Kc, that varies by growth stage (Allen et al., 1998). Tomato, for example, has a Kc of about 0.6 at establishment, rising to 1.15 at mid-season, and falling to 0.8 at late season. Onion has a lower Kc and a shallower root system, making it more sensitive to water stress at bulb formation. Understanding these stages is essential for deficit irrigation: stress at a tolerant stage costs little yield, while stress at a sensitive stage costs a lot (Geerts and Raes, 2009).

Water productivity, WP, is defined as yield divided by water applied or consumed, in kilograms per cubic metre (Fereres and Soriano, 2007). It is a more useful metric for water-scarce farmers than yield per hectare alone, because water, not land, is often the limiting resource. A farmer with 1,000 cubic metres of water can either irrigate 0.2 hectares at full ETc and obtain maximum yield per hectare, or irrigate 0.3 hectares at 70 percent ETc and obtain slightly lower yield per hectare but higher total production and income. Deficit irrigation is therefore an area-expansion strategy as much as a water-saving strategy (Gebrehiwot et al., 2021).

Soil and mulching mediate water productivity. Sandy soils drain quickly and require frequent, small irrigations, while clay soils hold water longer but can waterlog. Mulching with straw, grass, or plastic reduces evaporation, suppresses weeds, moderates soil temperature, and improves infiltration, and it is especially valuable with drip irrigation because the soil surface between rows remains dry (Assefa et al., 2022). Raised beds improve drainage for onion and reduce waterlogging, while tied ridges and basins can capture rainfall to supplement irrigation.

3. Drip Irrigation: Types, Performance and Fertigation

Drip irrigation has three main forms: surface drip, subsurface drip, and low-cost gravity-fed kits. Surface drip places laterals on the soil surface with emitters at each plant. It is the most common, easiest to install and maintain, and suitable for tomato, pepper, and cabbage. Subsurface drip buries laterals below the surface, reducing evaporation further and allowing mechanisation, but it is more costly, harder to repair, and vulnerable to root intrusion and clogging. Gravity-fed kits, often comprising a tank, filter, mainline, and drip lines for 0.05 to 0.25 hectares, require no pump or electricity and are the most accessible entry point for smallholders (Burney et al., 2010).

Performance evidence is strong. Assefa et al. (2022) conducted field-scale experiments in Ethiopia and Ghana on vegetable home gardens and found that drip irrigation combined with conservation practices reduced irrigation water use by 18 to 46 percent and increased yields by 9 percent to about two-fold compared with conventional tillage and furrow irrigation. The gains came not only from water delivery but also from reduced weed pressure, better soil moisture, and more uniform growth. Similar results have been reported for tomato in Benin, where drip irrigation under greenhouse and open field improved water productivity and reduced water use compared with furrow irrigation.

Fertigation, delivering soluble fertiliser through drip lines, is a major advantage. It places nutrients directly in the root zone, reduces leaching and volatilisation, and allows small, frequent doses matched to crop demand (Fereres and Soriano, 2007). For tomato, fertigation with nitrogen and potassium at flowering and fruiting can improve fruit size, firmness, and soluble solids. It requires clean water, filtration to prevent clogging, and careful calculation to avoid salt build-up. Farmers should flush lines regularly, check emitters for clogging, and avoid using fertilisers that precipitate in hard water.

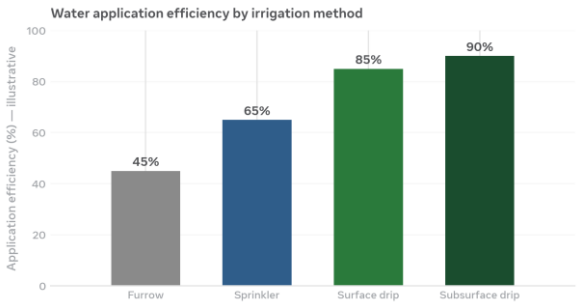


Figure 1. Illustrative water application efficiency by irrigation method. Drip methods typically achieve higher efficiency than furrow or sprinkler because water is delivered directly to the root zone (Fereres and Soriano, 2007). Values are illustrative, not measured trial means.

4. Deficit Irrigation: When Less Water Produces More Value

Deficit irrigation has two main forms: sustained deficit irrigation, where a constant fraction of ETc is applied throughout the season, and regulated deficit irrigation, where full irrigation is applied at sensitive stages and deficit at tolerant stages (Geerts and Raes, 2009). For tomato, the most sensitive stages are flowering and fruit set, while the vegetative stage and late ripening are more tolerant. For onion, bulb formation is sensitive, while early vegetative growth is more tolerant. For pepper, flowering and fruit expansion are sensitive. Timing therefore matters more than the average deficit.

A critical review of deficit irrigation in Ethiopia, based on 90 papers, found that for tomato the highest water productivity, 7.0 kg m-3, was at 70 percent ETc, followed by 50 percent ETc at 7.0 kg m-3 and 85 percent ETc at 6.9 kg m-3, while 100 percent ETc had the lowest water productivity at 6.8 kg m-3 (Gebrehiwot et al., 2021). For onion, water productivity decreased as irrigation increased from 60 percent ETc, at 1.8 kg m-3, to 100 percent ETc, at 1.3 kg m-3. These results do not mean that full irrigation is wasteful; they mean that the last 30 percent of water produces a disproportionately small increase in yield, and that water can often be used more profitably elsewhere.

A meta-analysis of eight crops from 62 Ethiopian studies confirmed this pattern. Applying deficit irrigation at 50 to 70 percent ETc in wheat increased water productivity by 48 percent with only 16 percent yield loss, and in tomato water productivity improved by 51 percent with 21 percent yield reduction (Desta et al., 2023). Sesame, tomato, and wheat showed the greatest resilience to water stress even at low deficit levels. The authors concluded that deficit irrigation could expand the area under irrigation by 100 to 137 percent for maize, 100 to 300 percent for wheat, 100 to 233 percent for onion, and 100 to 134 percent for tomato and teff for the same quantity of water, a powerful argument for water-scarce systems.

Quality effects are important and often favourable. Moderate deficit can increase tomato soluble solids, lycopene, and vitamin C, improve fruit firmness, and reduce cracking and blossom-end rot if calcium supply is adequate (Fereres and Soriano, 2007). Severe deficit, especially at flowering, can reduce fruit size, increase blossom-end rot, and reduce marketable yield. For onion, severe deficit can reduce bulb size and increase pungency, which may be desirable or undesirable depending on market preference. Farmers should therefore not apply a blanket deficit, but a stage-specific deficit, and should monitor fruit and bulb quality, not only weight.

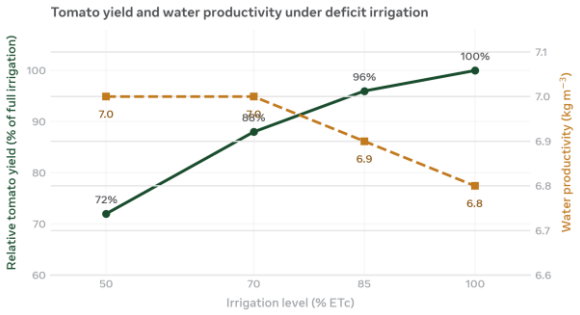


Figure 2. Illustrative tomato yield under deficit irrigation. Yield falls modestly at 70–85% ETc but water productivity rises, allowing a larger area to be irrigated (Gebrehiwot et al., 2021; Desta et al., 2023). Yield values are illustrative; water-productivity values are those reported for tomato in Gebrehiwot et al. (2021).

Table 1. Stage-specific deficit irrigation guidance for common vegetables.

Crop	Sensitive stages (full water)	Tolerant stages (deficit OK)	Practical deficit guidance
Tomato	Flowering, fruit set	Vegetative, late ripening	70-85% ETc, protect flowering
Onion	Bulb formation, expansion	Early vegetative	60-80% ETc, protect bulbing
Pepper	Flowering, fruit expansion	Vegetative, late harvest	70-85% ETc, protect flowering
Cabbage	Head formation	Early vegetative	70-85% ETc, protect head formation
Leafy vegetables	Throughout (short cycle)	—	Avoid severe deficit, short cycle

5. Scheduling, Solar Pumps and Maintenance

Scheduling is the decision of when and how much to irrigate. Simple methods are often sufficient: the feel-and-appearance method, tensiometers, and wetting-front detectors can indicate soil moisture without expensive equipment. More advanced methods use weather data, ETo, and crop coefficients, or soil moisture sensors connected to mobile phones. For smallholders, a practical rule is to irrigate frequently and in small amounts with drip, to keep the root zone moist but not saturated, and to reduce irrigation on cloudy days and after rain (Allen et al., 1998; Fereres and Soriano, 2007).

Solar pumps have transformed smallholder irrigation by removing fuel cost and allowing pumping from shallow wells, rivers, and tanks (Burney et al., 2010). A solar pump paired with a gravity-fed drip kit can irrigate 0.1 to

0.5 hectares without grid electricity, and it can be shared by a group. The economics depend on pump cost, panel cost, water depth, and crop value. Pay-as-you-go financing, group ownership, and hire services can make solar pumps accessible to farmers who cannot afford upfront purchase. Water governance is essential: if many farmers pump from the same aquifer, water tables can fall, so community rules on pumping hours, spacing, and monitoring are needed.

Maintenance determines whether drip systems survive. Clogging by sediment, algae, and mineral deposits is the most common failure. Filtration, regular flushing, and chlorination where appropriate can prevent clogging. Rodents, UV degradation, and physical damage can puncture lines, so lines should be protected, stored out of sun when not in use, and repaired promptly. Training on maintenance, spare parts availability, and local repair services are as important as the initial installation (Burney et al., 2010).

6. Economics, Gender, Adoption and Markets

Economics must be explicit. A drip kit for 0.1 hectares costs tens to hundreds of dollars, depending on type and country, while a solar pump costs hundreds to thousands. The return comes from higher yield, higher quality, dry-season production when prices are high, and lower labour for watering. Burney et al. (2010) found that smallholder drip irrigation in Niger increased incomes and food security, especially for women, because vegetables could be grown in the dry season when prices and nutritional need are highest. Similar results have been reported in Kenya, Tanzania, and Ethiopia, where solar drip kits increased farmer incomes by two to three times in some programmes, though results vary with market access.

Adoption is shaped by water access, land tenure, labour, and knowledge. Farmers adopt drip when they have a reliable water source, when they can sell vegetables at a profit, and when they see a neighbour succeed. They dis-adopt when lines clog, when pumps fail, when water runs out, or when markets collapse. Women often manage vegetable plots and watering, yet they may not control decisions about pump purchase or land use (FAO, 2020). Programmes that channel kits, training, and credit through women's groups, cooperatives, and youth enterprises are more likely to reach those who actually irrigate and to sustain adoption after project funding ends.

Table 2. Smallholder drip irrigation systems and their suitability.

System	Typical area	Water source	Strength / Limitation
Bucket + drip kit	0.05-0.1 ha	Tank, well	Low cost, low labour; small area
Gravity-fed drip	0.1-0.25 ha	Tank on stand	No energy, simple; needs elevation
Solar pump + drip	0.1-0.5 ha	Well, river, tank	No fuel, scalable; higher cost, needs maintenance
Diesel pump + drip	0.25-1 ha	Well, river	High output; fuel cost, pollution
Community scheme	1-10 ha	Dam, borehole	Large area; needs governance, fees

7. Research and Policy Priorities

Several gaps remain. First, long-term, multi-location trials that combine drip, deficit, mulching, and fertigation for different vegetables and soils are still scarce in semi-arid SSA. Second, research on low-cost scheduling, including soil moisture sensors and mobile advisories in local languages, should be prioritised. Third, economics research should measure not only yield but also water productivity, labour, income, and nutrition over multiple seasons. Fourth, research on groundwater sustainability, on pump governance, and on gender and youth should be embedded in irrigation trials, not treated as separate studies.

Policy should align incentives with water productivity. Public investment should support water harvesting, shallow wells, and solar pump financing, with safeguards for groundwater. Standards for drip kits should be enforced so farmers are not sold low-quality emitters that clog quickly. Extension should teach scheduling, maintenance, and deficit timing, not only installation. Market linkages, including cold storage, transport, and contracts with buyers, can ensure that higher vegetable production translates into higher income, not lower prices from gluts (FAO, 2020).

8. Conclusion

Drip irrigation and deficit irrigation, used together, offer a practical path to more vegetable production with less water in semi-arid SSA. Drip irrigation can reduce water use by 18 to 46 percent while increasing yields (Assefa et al., 2022), and deficit irrigation at 70 to 85 percent ETc can increase water productivity with only modest yield loss, allowing a larger area to be irrigated with the same water (Gebrehiwot et al., 2021; Desta et al., 2023). The challenge is not a lack of technology; it is the challenge of making low-cost kits, solar pumps, maintenance, and scheduling knowledge available to millions of smallholders, especially women and youth who grow vegetables. If that is achieved, drip plus deficit irrigation can turn water scarcity from a constraint into a managed resource, and vegetables from a risky seasonal crop into a reliable source of income and nutrition.

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Conflict of Interest

The authors declare no conflict of interest.

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