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Drip irrigation in tea (*Camellia sinensis*): Enhancing water use efficiency and sustainable production in Assam and Darjeeling

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Abstract

Drip irrigation has emerged as an efficient and sustainable water management practice in tea cultivation, particularly under changing climatic conditions and increasing water scarcity. Tea (*Camellia sinensis*) requires a continuous and balanced moisture supply for optimum shoot growth, yield, and quality. Traditional irrigation methods such as flood, furrow, and overhead sprinkler systems often result in substantial water loss through evaporation, runoff, nutrient leaching, and uneven moisture distribution. In contrast, drip irrigation delivers water directly to the root zone, significantly enhancing water-use efficiency and reducing wastage. Studies indicate that drip systems can achieve irrigation efficiencies of up to 90%, along with considerable savings in water, labour, and energy.

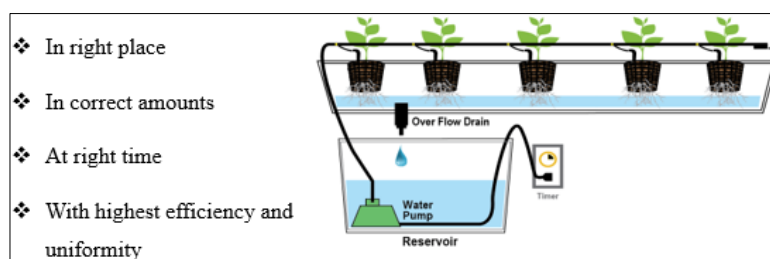
In tea-growing regions such as Assam and Darjeeling, where rainfall patterns have become increasingly erratic due to climate variability, drip irrigation serves as an effective supplemental irrigation strategy. It helps maintain uniform soil moisture during dry spells, supports continuous flushing, and improves overall crop productivity. The integration of fertigation through drip systems further enhances nutrient-use efficiency by supplying water-soluble fertilizers directly to the active root zone, reducing fertilizer losses and promoting better plant growth. Despite higher initial installation costs, the long-term economic benefits, including improved yield, reduced input costs, and enhanced sustainability, make drip irrigation a viable investment for tea plantations. Therefore, drip irrigation represents a climate-resilient and resource-efficient approach for sustainable tea production.

Keywords: Tea, drip irrigation, fertigation

Introduction

Drip irrigation is a type of micro-irrigation system that has the potential to save water and nutrients by allowing water to drip slowly to the roots of plants, either from above the soil surface or buried below the surface. The goal is to place water directly into the root zone and minimize evaporation. Drip irrigation systems distribute water through a network of valves, pipes, tubing, and emitters (FAO, 2012) [7]. Depending on how well designed, installed, maintained, and operated it is, a drip irrigation system can be more efficient than other types of irrigation systems, such as surface irrigation or sprinkler irrigation (Borthakur & Saikia, 2019) [3].

Drip irrigation is a production tool which delivers water, plant nutrients and chemicals



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Primitive drip irrigation has been used since ancient times in China during the first century by buried unglazed clay pots filled with water referred as *Ollas*, as a means of irrigation. Modern drip irrigation began its development in Germany in 1860 when researchers began experimenting with subsurface irrigation using clay pipe to create combination of irrigation and drainage systems. The usage of plastic to hold and distribute water in drip irrigation was later developed in Australia by Hannis Thill. Usage of a plastic emitter in drip irrigation was developed in Israel by Simcha Blass and his son. Instead of releasing water through tiny holes easily blocked by tiny particles, water was released through larger and longer passage ways by using friction to slow water inside a plastic emitter. The first experimental system of this type was established in 1959 by Blass, who partnered later (1964) with Kibbutz Hatzerim to create an irrigation company called Netafim. Together they developed and patented the first practical surface drip irrigation emitter.

Efficiency of drip irrigation

Irrigation efficiency (%) of different irrigation methods, showing a progressive improvement in water-use efficiency from conventional surface irrigation to advanced micro-irrigation systems. Irrigation efficiency refers to the proportion of applied water that is effectively utilized by plants for growth and physiological processes.

Among the traditional methods, flood irrigation exhibits the lowest efficiency, averaging about 32%, primarily due to substantial water losses through runoff, deep percolation, and evaporation. Furrow or basin irrigation improves efficiency slightly to approximately 45%, as water distribution is more controlled but still subject to significant losses (Bhattarai *et al.*, 2006) ^[2].

Pressurized irrigation systems demonstrate higher performance. The rain gun system achieves around 50% efficiency, while overhead sprinklers further enhance efficiency to nearly 60% by distributing water more uniformly across the field surface. Micro-sprinkler irrigation shows a marked improvement, reaching about 80% efficiency, owing to reduced evaporation losses and localized water application.

The highest efficiency is observed in drip irrigation, with values close to 90%. This system delivers water directly to the root zone, minimizing wastage and improving water productivity. The figure also indicates that drip irrigation can effectively irrigate nearly twice the area compared to conventional systems, while sprinkler systems irrigate approximately 1.5 times the area using the same quantity of water.

Drip irrigation in tea

To get stable yield and quality of tea, tea garden needs timely and appropriate irrigation. Sprinkler irrigation/ overhead irrigation system is generally used in tea garden. By which water is distributed in the air as droplets over a circular area. Drip irrigation technology leads to significant savings in water, fertilizer and labour. It increases the yield and also the crop quality. From economic side of view, it is the most sustainable system for tea plantation delivering higher economic returns than other irrigation methods (Kumar & Ahmed, 2014, Narayanamoorthy, 2004) ^[10, 13].

Tea production is significantly influenced by seasonal climatic conditions, which act as limiting factors affecting plant growth and productivity. During the dry season, tea plants are highly sensitive to water deficit and moisture stress, leading to reduced nutrient availability and uptake due to low soil moisture. This condition suppresses shoot growth and lowers yield potential. In

contrast, the wet season presents challenges such as waterlogging, which hampers root respiration and nutrient absorption. Excess rainfall further results in nutrient leaching, surface runoff, and deep percolation losses, thereby reducing soil fertility and overall nutrient use efficiency. (Bhagat *et al.*, 2010) ^[1].

First drip irrigation in Tea was started in Tanzania, an African country near to Sahara. This will result into low or poor crop productivity and drying of available water sources due to increasing global climate change and inefficient use of irrigation water in tea. Because of that Tea Research Institute of Tanzania (TRIT), through Crop Water Management Programme conducted research on the efficiency of using drip irrigation in tea production to large scale and small holder tea growers in Tanzania.

Drip irrigation in Darjeeling

Tea cultivation in the Himalayan hills of Darjeeling is traditionally rain-fed and highly dependent on well-distributed precipitation. However, recent climatic variability characterized by declining rainfall, rising temperature, and prolonged dry periods has created severe soil-moisture stress in tea plantations. Studies and field observations indicate that annual rainfall patterns have become increasingly erratic, with early-season drought conditions significantly reducing first-flush production and overall yield stability. A rainfall deficit of nearly 22% over recent decades has been reported, resulting in moisture depletion and reduced shoot growth in tea bushes.

Tea plants require continuous moisture for active flushing, and insufficient water availability directly affects both yield and quality. Research conducted at the Darjeeling Tea Research and Development Centre showed that increasing temperature and decreasing rainfall have contributed to reduced green-leaf productivity per hectare. Extended drought periods and declining relative humidity negatively influence plant physiology, emphasizing the need for supplemental irrigation strategies in hill tea systems (Choubey, 2018) ^[5].

Unlike plains tea regions, irrigation development in Darjeeling faces unique constraints due to steep slopes, shallow soils, and limited groundwater availability. Tea estates largely depend on natural springs and rainfall harvesting rather than conventional canal irrigation. Some estates have therefore adopted localized self-irrigation systems by channelling spring water and installing sprinklers or pipelines to maintain soil moisture during dry months (Majumder, 2018) ^[12]. Increasing drying of natural water sources and forest degradation have further forced growers to consider artificial irrigation methods to sustain crop survival (The week, 2025) ^[15].

Under such fragile hill conditions, drip irrigation is increasingly recognized as a suitable alternative because it delivers water directly to the root zone, minimizing runoff and soil erosion—major concerns in sloping tea gardens. Drip systems can maintain uniform soil moisture, improve water-use efficiency, and support continuous flushing during pre-monsoon drought periods. This approach is particularly relevant in Darjeeling, where tea bushes require regular moisture supply between October and March, when only a small proportion of annual rainfall occurs (India climate dialogue, 2019) ^[8].

Although large-scale adoption remains limited due to installation cost and terrain challenges, drip irrigation combined with rainwater harvesting, mulching, and soil conservation practices is increasingly viewed as a climate-resilient adaptation strategy. With ongoing climate change affecting temperature and rainfall variability, efficient micro-irrigation technologies are expected to play a crucial role in sustaining both productivity and the premium quality associated with Darjeeling tea.

Drip irrigation in Assam

Tea cultivation in Assam represents one of the largest tea-growing ecosystems in the world, contributing significantly to India's total tea production. Unlike hill tea regions, Assam tea is grown under humid tropical conditions; however, productivity is strongly influenced by seasonal rainfall variability. Despite receiving high annual rainfall, prolonged dry spells during the pre-monsoon period (February–April) frequently create soil moisture stress, leading to reduced flushing rate and decline in green-leaf yield (Carr, 2010) [4].

Tea plants require continuous soil moisture for optimum shoot growth and biochemical development. Studies have shown that moisture stress reduces photosynthetic activity, stomatal conductance, and nutrient uptake, ultimately affecting yield and quality parameters. Traditional reliance on rainfall makes Assam tea vulnerable to climate variability, especially when delayed monsoon onset coincides with high evapotranspiration demand. Under such conditions, supplemental irrigation becomes essential for sustaining productivity (Kigalu *et al.*, 2008) [9].

Drip irrigation has gained attention as an efficient micro-irrigation technique capable of improving water-use efficiency in tea plantations. Research conducted in tea estates of Northeast India demonstrated that drip irrigation maintains uniform soil moisture near the active feeder roots, resulting in improved shoot density and increased made-tea yield compared with rain-fed conditions. Water savings of 30–50% have been reported when drip irrigation replaces conventional sprinkler systems, while fertigation through drip lines enhances nutrient-use efficiency and reduces fertilizer losses.

Field evaluations further indicate that drip irrigation improves crop water productivity and stabilizes yield during drought periods. Maintaining optimum soil moisture also supports continuous flushing cycles, which is critical for CTC tea production dominant in Assam. Additionally, drip systems reduce weed growth between rows and minimize soil compaction caused by frequent irrigation operations.

However, adoption in Assam tea gardens is still limited due to initial installation cost, maintenance requirements, and the perception that high rainfall eliminates irrigation needs. Recent climate trends showing irregular rainfall distribution and increasing temperature highlight the growing importance of precision irrigation technologies. Integration of drip irrigation with mulching and soil moisture conservation practices is therefore considered a sustainable strategy for enhancing resilience of Assam tea plantations under changing climatic conditions (TRA, 2018) [14].

Limitations of overhead sprinkler irrigation systems

Overhead sprinkler irrigation often results in inefficient water utilization and uneven field performance. One of the primary problems is poor overlap of sprinkler patterns under high wind conditions, which causes non-uniform water application across the field. This leads to areas receiving excess water while others remain under-irrigated.

The system also requires high operating pressure, increasing energy consumption and operational costs. Excess water application contributes to nutrient leaching, resulting in low fertilizer use efficiency (FUE), where essential nutrients move beyond the root zone and become unavailable to plants (Das *et al.*, 2019) [6].

Another critical concern shown is soil erosion and surface runoff, especially in sloped plantation areas. These processes not only waste irrigation water but also degrade soil structure and reduce long-term productivity. Additionally, overhead sprinklers

promote erratic water distribution, creating sloppy or waterlogged patches that lower overall water use efficiency (WUE).

Because water is mainly applied at the surface, the system may also lead to poor effective root volume development, as moisture does not consistently reach deeper root zones.

Fertigation

Fertigation is a method of fertilizer application in which fertilizer is incorporated within the irrigation water by the drip system. In this system fertilizer solution is distributed evenly in irrigation. The availability of nutrients is very high therefore the efficiency is more. In this method liquid fertilizer as well as water soluble fertilizers are used. By this method, fertilizer use efficiency is increased up to 80 to 90 percent.

Advantages of fertigation

Nutrients and water are supplied near the active root zone through fertigation which results in greater absorption by the crops. As water and fertilizer are supplied evenly to all the crops through fertigation there is possibility for getting 25-50 per cent higher yield. Fertilizer use efficiency through fertigation ranges between 80-90 per cent, which helps to save a minimum of 25 per cent of nutrients. By this way, along with less amount of water and saving of fertilizer, time, labour and energy use is also reduced substantially.

Fertilizer used in fertigation

Urea, potash and highly water-soluble fertilizers are available for applying through fertigation. Application of super phosphorus through fertigation must be avoided as it makes precipitation of phosphate salts. Thus, phosphoric acid is more suitable for fertigation as it is available in liquid form (Kumar *et al.*, 2017) [11]. Special fertilizers like mono ammonium phosphate (Nitrogen and Phosphorus), poly feed (Nitrogen, Phosphorus and Potassium), Multi K (Nitrogen and Potassium), Potassium sulphate (Potassium and Sulphur) are highly suitable for fertigation, as they are highly soluble in water. Fe, Mn, Zn, Cu, B, Mo are also supplied along with special fertilizers.

Fertilizer efficiencies of various application methods

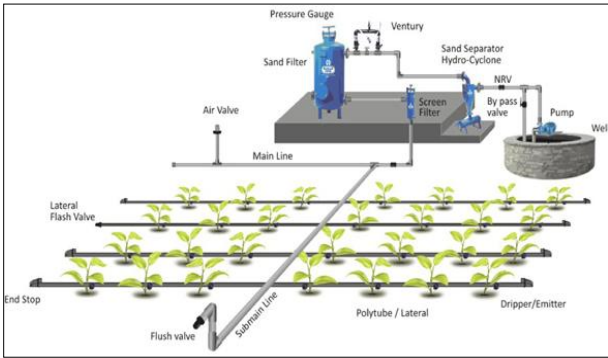
Nutrient	Fertilizer use efficiency (%)	
	Soil application	Fertigation
Nitrogen	30-50	95
Phosphorous	20	45
Potassium	50	80

Components of drip irrigation

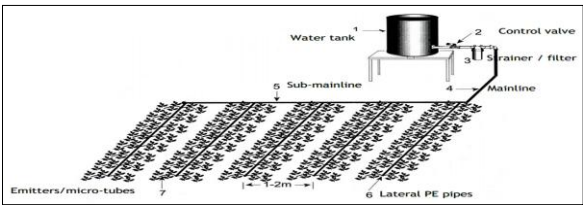
- Pump or pressurized water source.
- Water filter(s) or filtration systems: sand separator, fertigation systems.
- Backwash controller (Backflow prevention device)
- Pressure control valve (pressure regulator)
- Distribution lines (main larger diameter pipe, maybe secondary smaller, pipe fittings)
- Hand-operated, electronic, or hydraulic control valves and safety valves
- Smaller diameter polyethylene tube (often called "laterals")
- Poly fittings and accessories (to make connections)
- Emitting devices at plants (emitter or dripper, micro spray head, inline dripper or inline drip tube)

Layout and Design

A) For Commercial drip irrigation



B) For Small scale and self-made drip irrigation



Cost–benefit components of drip irrigation in tea (*Camellia sinensis*) production

Component	Conventional Irrigation / Rainfed System	Drip Irrigation System	Economic Implication
Initial Investment	Low or negligible	High initial cost (installation of pipes, emitters, filters, fertigation unit)	Higher capital requirement but long service life (8–12 years)
Water Use	High water loss through evaporation, runoff, and deep percolation	30–50% water saving due to localized application	Reduced irrigation cost and improved water productivity
Fertilizer Use Efficiency	Nutrient loss through leaching and runoff	Fertigation improves nutrient delivery (20–40% fertilizer saving)	Lower fertilizer expenditure and improved nutrient uptake
Labour Requirement	Higher labour for irrigation management	Reduced manual irrigation operations	Lower recurring labour cost
Soil Moisture Condition	Uneven moisture distribution	Uniform root-zone moisture	Improved plant growth and flushing frequency
Yield Performance	Seasonal fluctuation, drought sensitivity	20–50% yield improvement reported in perennial crops	Increased annual income
Weed Growth	Higher due to full-surface wetting	Reduced weed growth	Lower weeding cost
Energy Consumption	Often higher due to inefficient water application	Controlled water delivery reduces pumping requirement	Energy savings over time
Environmental Impact	Nutrient leaching and soil erosion common	Reduced runoff and nutrient loss	Sustainable soil and water management
Benefit–Cost Ratio	Moderate	Typically, 1.5–1.9 (varies by region and subsidy support)	Economically viable long-term investment
Payback Period	Not applicable	Approx. 2–6 years (shorter with subsidy schemes)	Profitable over plantation lifespan

Conclusion

Drip irrigation technology significantly enhances the efficient use of natural resources, including water, energy, labour, and fertilizers, making it highly suitable for tea plantation systems. It performs effectively under tea-growing conditions by maintaining optimal soil moisture and supporting consistent plant growth, while the integration of fertigation further contributes to increased yield and improved nutrient uptake. The use of low-discharge drippers enhances fertigation efficiency by minimizing nutrient losses through leaching and ensuring precise delivery to the root zone. In the context of global warming and increasing water scarcity, drip irrigation emerges as a highly effective and sustainable approach for improving productivity and resource conservation in tea cultivation.

Future prospects

The future of tea cultivation increasingly depends on sustainable water and resource management practices, making drip irrigation a highly promising solution. With growing concerns over excessive groundwater extraction, the adoption of drip irrigation can significantly reduce water use by delivering it precisely to the root zone. This method also minimizes runoff and nutrient leaching, thereby helping to prevent soil erosion and maintain soil health. Additionally, labour scarcity remains a major challenge in tea plantations; however, the use of drip irrigation combined with fertigation can reduce manual labour requirements by automating water and nutrient application. Overall, these advantages highlight drip irrigation as a key strategy for ensuring long-term sustainability and resilience in tea production systems.

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