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Water and nutrient management in mulberry: A review

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Abstract

Mulberry (*Morus* spp.) is the sole food source for the silkworm *Bombyx mori* L., and the productivity and quality of mulberry leaves directly influence the cocoon yield and silk production. Efficient management of water and nutrients is therefore essential for sustaining mulberry productivity under changing climatic conditions and increasing resource constraints. This review summarizes the factors influencing water use efficiency (WUE) and nutrient use efficiency (NUE) in mulberry cultivation, including crop genotype, soil characteristics, climate, irrigation practices and nutrient management strategies. Recent advances in irrigation methods such as drip and subsurface drip irrigation, sensor-based irrigation and hydrogel application have significantly improved water productivity and reduced irrigation requirements. Similarly, integrated nutrient management practices including balanced fertilization, fertigation, micronutrient supplementation and biofertilizers have enhanced leaf yield, leaf quality and nutrient uptake efficiency. Studies also highlight the role of improved genotypes, organic inputs and precision agriculture technologies in optimizing resource use efficiency. Overall, efficient water and nutrient management practices play a crucial role in improving mulberry growth, leaf productivity and cocoon yield while ensuring sustainable sericulture production system.

Keywords: Water, nutrient, irrigation, fertigation, mulberry, silkworm

Introduction

Mulberry is a robust, perennial deep-rooted foliage yielding plant, which produces high biomass and grows from the tropics to the temperate region throughout the year. The mulberry silkworm, being a monophagous insect, depends solely on mulberry for its growth and development. Approximately 70% of silk proteins are derived from proteins present in mulberry leaves. Silkworms must therefore be nourished with good quality mulberry leaves in sufficient quantity for obtaining sustained productivity of quality cocoons. Different factors responsible for a successful cocoon crop are mulberry leaf (38.2%), micro-climate (37%), rearing technique (9.3%), silkworm race (4.2%), silkworm eggs (3.0%) and other factors (8.2%) (Miyashita, 1986). It indicates that the quantity and quality of leaf produced per unit area have a direct effect on quantity and quality of cocoons. Mulberry is known to respond very well to various inputs, particularly to the soil moisture and nutrients. Both these factors are interrelated and are complementary to each other. Nutrients are taken up by the plants in solution form for which soil moisture is important. The sustainability of mulberry production system requires optimum utilization of resources such as water, fertilizer or soil. At present, about 95% of mulberry region is under the irrigated condition and borewell water is a common source of irrigation in South India. With change in climate scenario, the water availability is getting scarce day by day due to quick ground water depletion which often constrains the farmers to irrigate their mulberry gardens as per requirements. Irrigation increased leaf yield of mulberry plants by about 68% (Sudhakar *et al.*, 2018) ^[70]. Hence, increase in leaf production and productivity of mulberry is possible by improved methods of irrigation. Granular or dry fertilizer application typically results in absorption rates of only 10 to 40% of applied fertilizers. Hence, it is essential to standardize the agro - techniques and technology innovations for mulberry cultivation to achieve higher mulberry productivity through better water and nutrient management strategies.

Factors Influencing Water Use Efficiency (WUE)

1. Climate and weather

Climatic conditions such as temperature, rainfall, humidity, and wind speed directly influence evapotranspiration and crop water use efficiency. Higher temperatures increase evaporation and plant transpiration rates, which can lead to greater water loss if not accompanied by proportional increases in biomass production (Mbava *et al.*, 2020) ^[38]. Rainfall patterns also determine the need for supplemental irrigation and affect soil moisture availability during crop growth. Atmospheric factors such as low humidity and strong winds enhance vapor pressure gradients between the leaf and atmosphere, increasing transpiration and reducing WUE under certain conditions (Blum, 2005) ^[4]. Therefore, climatic variability is considered one of the primary environmental factors regulating water productivity in cropping systems (Hatfield and Dold, 2019) ^[21].

2. Land topography

Land topography affects the distribution, movement, and retention of water within agricultural fields, thereby influencing water use efficiency. On sloping lands, water may flow rapidly as surface runoff, leading to uneven water distribution and reduced soil moisture availability for crops. In contrast, relatively flat terrain allows more uniform infiltration and water retention (Pandey *et al.*, 2003) ^[45]. Farmers often adopt land management practices such as terracing, contour farming, or land levelling to improve water distribution and enhance water use efficiency in sloping landscapes (Speelman *et al.*, 2008; Kotze *et al.*, 2024) ^[69, 29].

3. Soil type and structure

Soil physical and chemical properties strongly influence water retention, availability, and movement within the soil profile, thereby affecting crop water use efficiency (Hatfield & Dold, 2019) ^[21]. Sandy soils generally have lower water-holding capacity and higher infiltration rates, which may lead to rapid drainage and reduced water availability for crops (Lal, 2009) ^[31]. In contrast, clay soils retain more water but may restrict aeration and root penetration if poorly structured. Well-aggregated soils with good porosity allow better root development and improve soil moisture storage, enabling plants to utilize water more efficiently (Mbava *et al.*, 2020) ^[38].

4. Crop type and variety

Crop type and genetic characteristics play a significant role in determining water use efficiency. Different crops and varieties possess varying physiological mechanisms such as stomatal regulation, photosynthetic efficiency and root architecture that influence how effectively water is converted into biomass or yield (Hatfield and Dold, 2019) ^[21]. Crop varieties with deeper and more extensive root systems can access water from deeper soil layers and sustain growth during moisture stress, thereby improving overall WUE (Zhang *et al.*, 2012) ^[75].

5. Water management practices

Efficient water management practices significantly influence crop water use efficiency by determining how and when water is supplied to crops. Irrigation methods such as drip and sprinkler irrigation deliver water precisely to the root zone and reduce losses due to evaporation, runoff and deep percolation compared with traditional irrigation methods. Proper irrigation scheduling based on crop growth stage and soil moisture conditions further enhances WUE (Narayanamoorthy, 2004) ^[40].

6. Water quality

Water quality also plays an important role in determining crop water use efficiency. Irrigation water containing high levels of salts or contaminants can negatively affect plant growth by causing osmotic stress and nutrient imbalances (Hatfield and Dold, 2019) ^[21]. Salinity reduces the ability of plants to absorb water from the soil, forcing them to use more water to maintain physiological functions. As a result, poor water quality can reduce crop productivity and lower overall water use efficiency (Ospanbayev *et al.*, 2017; Mbava *et al.*, 2020) ^[43, 38].

7. Farming practices

Agronomic practices such as mulching, conservation tillage, crop rotation and intercropping greatly influence soil moisture conservation and water use efficiency (Lithourgidis *et al.*, 2011) ^[32]. Mulching reduces soil evaporation and maintains favourable temperature and moisture conditions. Conservation tillage improves soil structure and organic matter content, enhancing water infiltration and storage capacity (Hobbs *et al.*, 2008) ^[25].

8. Technological innovations

Advances in agricultural technology have contributed significantly to improving water use efficiency. Precision agriculture technologies such as soil moisture sensors, remote sensing and automated irrigation systems enable farmers to monitor crop water status and apply irrigation more accurately (Gebbers and Adamchuk, 2010) ^[10]. These technologies help reduce unnecessary water use and improve irrigation efficiency.

9. Economic and policy factors

Socio-economic and policy factors also influence how efficiently water is used in agriculture. Water pricing policies, irrigation subsidies and water rights regulations shape farmers' decisions regarding irrigation practices and water conservation measures (Wang, 2010) ^[74]. Studies have shown that farmer education, access to extension services and farm size significantly influence irrigation water use efficiency (Speelman *et al.*, 2008; Kotze *et al.*, 2024) ^[69, 29].

Factors Influencing Nutrient Use Efficiency (NUE)

1. Soil properties

Soil properties play a fundamental role in determining nutrient use efficiency. Soil fertility status, organic matter content and pH directly influence nutrient availability and uptake by plants (Dobermann and Cassman, 2002; Prasad, 2009) ^[8, 47]. Soils rich in organic matter enhance nutrient retention and microbial activity, improving nutrient availability to crops (Lal, 2009) ^[31, 47].

2. Soil microbial activity

Soil microorganisms such as bacteria, fungi and actinomycetes play a crucial role in nutrient cycling and nutrient availability (Vessey, 2003) ^[72]. These microbes decompose organic matter and convert nutrients into plant-available forms through processes such as mineralization and nitrification (Graham and Vance, 2003; Ladha *et al.*, 2005) ^[14, 30].

3. Environmental conditions

Environmental factors such as temperature, rainfall and solar radiation strongly influence nutrient availability and plant uptake (Aulakh and Malhi, 2005) ^[3]. Temperature regulates microbial processes such as mineralization, while soil moisture affects nutrient diffusion to plant roots (Ladha *et al.*, 2005) ^[30].

4. Crop type and variety

Different crop species and varieties differ in their nutrient requirements and nutrient uptake efficiency. Genetic differences influence root architecture, nutrient absorption capacity and nutrient utilization efficiency (Hirel *et al.*, 2011; Graham and Vance, 2003) ^[23, 14].

5. Agronomic practices

Agronomic practices such as crop rotation, intercropping, mulching and conservation tillage improve soil fertility and nutrient cycling (Lithourgidis *et al.*, 2011) ^[32]. Integrated nutrient management combining organic and inorganic fertilizers enhances soil fertility and nutrient use efficiency (Palm *et al.*, 2014; Parven *et al.*, 2020) ^[44, 46].

6. Fertilizer management

Efficient fertilizer management practices including proper timing, rate and placement of fertilizers are essential for improving NUE (Hebbar *et al.*, 2004) ^[22]. Controlled-release fertilizers and fertigation techniques help reduce nutrient losses and increase nutrient availability near the root zone (Dobermann and Cassman, 2002; Fageria and Baligar, 2005) ^[8, 9].

7. Nutrient interactions

Interactions among nutrients influence nutrient availability and uptake efficiency. Excessive application of one nutrient may suppress the uptake of another due to antagonistic interactions, while synergistic relationships may enhance plant growth (Aulakh and Malhi, 2005; Rietra *et al.*, 2017) ^[3, 58].

8. Management of nutrient losses

Losses of nutrients through leaching, runoff and volatilization significantly reduce nutrient use efficiency. Improved management strategies such as split fertilizer application, use of inhibitors and proper irrigation practices help reduce nutrient losses (Dobermann and Cassman, 2002; Ladha *et al.*, 2005) ^[8, 30].

9. Technological innovations

Precision agriculture technologies including remote sensing, GPS-based nutrient mapping and soil sensors allow farmers to apply fertilizers more accurately based on crop requirements (Gebbers and Adamchuk, 2010) ^[10]. Biofertilizers and nanotechnology-based fertilizers also improve nutrient availability and NUE (Jat *et al.*, 2013; Sekhon, 2014) ^[26, 61].

10. Farmer knowledge and management practices

Farmer knowledge and adoption of improved agricultural practices significantly influence nutrient use efficiency. Farmers who practice soil testing, balanced fertilization and site-specific nutrient management can significantly improve fertilizer use efficiency (Prasad, 2009; Jat *et al.*, 2013) ^[47, 26].

Table 1: Irrigation requirement of mulberry

Irrigation details	Black clay soil	Red loamy soil	Sandy soil
Frequency	12 days	10 days	8 days
No. of irrigation per crop	6	7	9
Total water required per crop (gallons)	1,98,000	2,31,000	2,97,000
Total water required per year per acre (5 crops) in gallons	9,90,000	11,55,000	14,85,000

Note: water requirement for one irrigation (1.5 acre inch) is 33,000 gallons (Dandin and Giridhar, 2014) ^[5]

Irrigation has a major role in increasing the productivity of an

area both in terms of increased yield of the crops and also in boosting multiple cropping. Among various agronomic inputs to which mulberry responds well and quickly, irrigation ranks high as it helps in better utilization of manures and fertilizers. Irrigation water must be treated as a precious input to the best advantage. In light sandy loam soils, irrigation once in 7-8 days interval may be necessary while in heavy clay loam soils, irrigation at 8-10 days interval is adequate. It is also important to supply adequate quantum of water at a time. It has been estimated that 1.5 acre inches of water per irrigation is required (1 acre inch = 22,687 gallons; 1 gallon = 4.55 litres) (Dandin and Giridhar, 2014) ^[5].

Table 2: Manure and fertilizer schedule for V₁ mulberry garden under irrigated condition

Crop	FYM (MT ha ⁻¹ year ⁻¹)	Fertilizer (kg per ha per crop)		
		N	P	K
First	10	70	28	28
Second	-	70	28	28
Third	-	70	28	28
Fourth	10	70	28	28
Fifth	-	70	28	28
Total	20	350	140	140

(Dandin and Giridhar, 2014) ^[5]

Farmyard manure/compost produced from sericultural agricultural wastes should be applied @ 20 MT per hectare per year, following bottom pruning when monsoon starts. Chemical fertilizers are applied in 5 or 6 split doses depending upon the number of shoot/leaf harvests, after 3-4 weeks of each harvest as per the schedule. Depending on the soil test results, appropriate chemical fertilizers should be applied in furrows of 5-8 cm deep and should be closed to avoid loss due to volatilization or weathering. Irrigation should be followed immediately after fertilizer application. Recommended dose of fertilizers is 350:140:140 kg NPK/ha/year in shoot harvest system (5 harvests) (Dandin and Giridhar, 2014) ^[5].

Different Ways to Improve Water Use Efficiency

1. Drip irrigation

Drip irrigation is one of the most effective methods for improving water use efficiency in agriculture. This method delivers water directly to the root zone of plants through a network of pipes and emitters, thereby minimizing evaporation, runoff and deep percolation losses. Because water is applied in small quantities at frequent intervals, crops can utilize it more efficiently compared to conventional surface irrigation methods (Narayanamoorthy, 2004) ^[40]. Studies have shown that drip irrigation significantly improves crop productivity while reducing water use in several cropping systems (Hatfield and Dold, 2019) ^[21].

2. Micro-irrigation systems

Micro-irrigation systems, including micro-sprinklers and subsurface drip irrigation, are designed to apply water precisely and uniformly to crops. These systems reduce water losses associated with conventional irrigation methods and ensure efficient utilization of available water resources (Singh *et al.*, 2024). Micro-irrigation has been reported to increase irrigation efficiency and crop productivity while conserving water in arid and semi-arid regions (Narayanamoorthy, 2004; Mbava *et al.*, 2020) ^[40, 38].

3. Soil moisture management

Efficient soil moisture management is crucial for improving

water use efficiency in crop production. Monitoring soil moisture levels using tools such as tensiometers, soil moisture sensors or gravimetric methods allows farmers to schedule irrigation based on crop requirements. Applying irrigation water only when soil moisture reaches critical levels prevents over-irrigation and reduces water wastage (Jones, 2004) ^[27].

4. Rainwater harvesting

Rainwater harvesting is an important strategy for improving water availability and water use efficiency in rainfed and semi-arid agricultural systems. Collection and storage of rainwater in farm ponds, tanks or reservoirs allows farmers to use stored water for supplemental irrigation during dry periods (Pandey *et al.*, 2003) ^[45]. This practice reduces dependency on groundwater and improves crop productivity (Speelman *et al.*, 2008; Kotze *et al.*, 2024) ^[69, 29].

5. Use of drought-tolerant crops

Cultivation of drought-tolerant crop varieties improves water use efficiency under water-limited conditions (Blum, 2005) ^[4]. These varieties possess physiological and morphological traits that enable them to withstand moisture stress and maintain productivity with lower water inputs (Zhang *et al.*, 2012; Hatfield and Dold, 2019) ^[21].

6. Conservation tillage

Conservation tillage practices such as reduced tillage or zero tillage improve soil moisture retention and reduce evaporation losses. Crop residues left on the soil surface act as mulch, protecting the soil and improving water infiltration and storage capacity (Hobbs *et al.*, 2008; Palm *et al.*, 2014) ^[25, 44].

7. Wetland and soil-based systems

Constructed wetlands and soil-based treatment systems can recycle agricultural wastewater and improve water use efficiency (Vymazal, 2011). These systems remove contaminants from water before it is reused for irrigation and help conserve freshwater resources (Pandey *et al.*, 2003; Hatfield and Dold, 2019) ^[45, 21].

8. Efficient fertilizer application

Efficient fertilizer management contributes indirectly to improved water use efficiency. Proper fertilizer placement, balanced nutrient application and fertigation ensure nutrients are available at the right time and in the right amounts (Dobermann and Cassman, 2002; Hebbar *et al.*, 2004; Fageria and Baligar, 2005) ^[8, 22, 9].

9. Crop rotation and intercropping

Crop rotation and intercropping improve soil structure, enhance soil organic matter and increase soil moisture retention capacity. Introducing legumes improves soil fertility and reduces water requirements for subsequent crops (Lithourgidis *et al.*, 2011; Palm *et al.*, 2014) ^[32, 44].

10. Precision agriculture

Precision agriculture technologies improve water use efficiency through site-specific irrigation management. Tools such as remote sensing, GPS-guided irrigation and soil moisture sensors allow farmers to apply water according to crop requirements (Gebbers and Adamchuk, 2010) ^[10].

Different Ways to Improve Nutrient Use Efficiency

1. Improved fertilizer management

Efficient fertilizer management improves nutrient use efficiency by ensuring that nutrients are applied according to crop demand

and soil nutrient status (Dobermann and Cassman, 2002) ^[8]. Precision fertilization, split application and controlled-release fertilizers reduce nutrient losses through leaching and volatilization (Fageria and Baligar, 2005; Jat *et al.*, 2013) ^[9, 26].

2. Optimizing soil health

Maintaining soil health enhances nutrient availability and retention. Organic amendments such as compost and manure improve soil structure, microbial activity and water-holding capacity (Lal, 2009; Prasad, 2009; Palm *et al.*, 2014) ^[31, 47, 44].

3. Crop rotation and diversification

Crop rotation and diversified cropping systems enhance nutrient cycling and soil fertility. Legumes fix atmospheric nitrogen and reduce the need for chemical fertilizers (Graham and Vance, 2003; Lithourgidis *et al.*, 2011) ^[14, 32].

4. Use of microbial inoculants

Biofertilizers improve nutrient availability and plant uptake efficiency (Vessey, 2003) ^[72]. Microorganisms such as Rhizobium and phosphate-solubilizing bacteria enhance nitrogen fixation and phosphorus availability (Ladha *et al.*, 2005; Sekhon, 2014) ^[30, 61].

5. Nutrient recycling

Nutrient recycling through cover crops and composting helps maintain soil fertility and reduce nutrient losses. Cover crops capture residual nutrients and prevent leaching during fallow periods (Palm *et al.*, 2014; Parven *et al.*, 2020) ^[44, 46].

6. Water and irrigation management

Efficient irrigation improves nutrient use efficiency by maintaining optimal soil moisture for nutrient transport and uptake. Techniques such as drip irrigation and fertigation deliver nutrients directly to the root zone (Hebbar *et al.*, 2004; Fageria and Baligar, 2005) ^[22, 9].

7. Genetic improvement of crops

Plant breeding and biotechnology have enabled development of nutrient-efficient crop varieties with improved root systems and nutrient uptake mechanisms (Ladha *et al.*, 2005; Hirel and Lea, 2011) ^[30, 23].

8. Smart monitoring and data-driven decisions

Precision agriculture technologies allow farmers to monitor soil nutrient status and apply fertilizers based on crop requirements. Remote sensing, satellite imagery and soil sensors improve fertilizer management efficiency (Gebbers and Adamchuk, 2010; Jat *et al.*, 2013; Sekhon, 2014) ^[10, 26, 61].

Water management in mulberry

Efficient Irrigation Systems

Different irrigation methods have been widely studied to improve water use efficiency and productivity in mulberry cultivation. Higher leaf yield (10,057.08 kg ha⁻¹ crop⁻¹) was recorded under subsurface drip irrigation at a depth of 1½ ft compared to flood irrigation (9,565.05 kg ha⁻¹ crop⁻¹). Leaf quality parameters such as moisture content (77.54%) and chlorophyll content (5.61 mg g⁻¹) were also increased under subsurface drip irrigation. The improvement was attributed to the efficient delivery of water directly to the rhizosphere zone, whereby evaporation losses were minimized and optimum soil moisture for root activity and nutrient uptake was maintained (Sudhakar *et al.*, 2018) ^[70]. Similarly, higher leaf yield (43,903

kg ha⁻¹ yr⁻¹) and cocoon yield (61 kg per 100 DFLs) were recorded under subsurface drip irrigation compared with other irrigation methods. The increase was due to improved soil

moisture availability and enhanced photosynthetic efficiency (Seenappa *et al.*, 2015) [52].

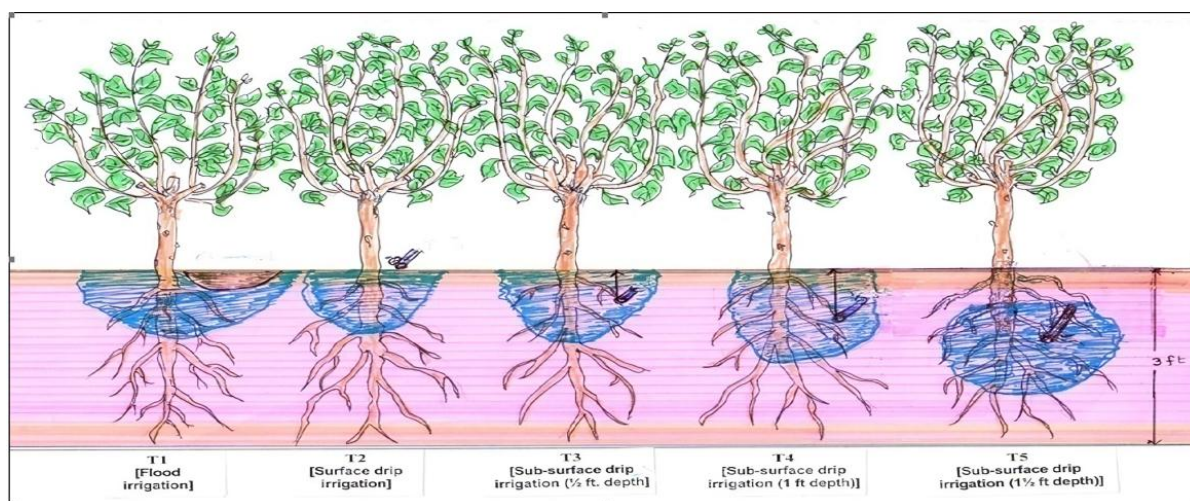


Fig 1: Tree mulberry with drips and water infiltration scenario in the rhizosphere zone of mulberry in varied irrigations (Sudhakar *et al.*, 2018) [70]

Irrigation scheduling and drip irrigation systems have also demonstrated significant improvements in water productivity and mulberry yield. About 61.2% irrigation water was saved through drip irrigation compared with farmers' practice, and higher leaf yield (64,377.16 kg ha⁻¹ year⁻¹) was recorded compared with 50,801.48 kg ha⁻¹ under conventional furrow irrigation (Rajaram *et al.*, 2017) [48]. Similarly, water use efficiency was improved by nearly 300% under drip irrigation while higher leaf yield was maintained compared with traditional irrigation systems. These improvements were mainly attributed to localized water application, reduced runoff and evaporation losses and efficient moisture management in the root zone (Rajaram and Qadri, 2014) [49].

Irrigation levels combined with mulching practices have also been found to significantly enhance mulberry growth and productivity. Irrigation at 0.8 CPE along with mulching was reported to record higher plant height (123.28 cm), number of shoots (23.70 plant⁻¹), leaves (315.74 plant⁻¹) and leaf yield (47,613 kg ha⁻¹). Leaf moisture (81.21%) and chlorophyll content (8.48 SPAD) were also found to be maximum compared with lower irrigation levels (Ranjitha and Chandrashekhar, 2021) [56]. Subsurface drip irrigation at 0.75 CPE was observed to record higher shoot length (143.33 cm) and number of leaves (350.96 plant⁻¹) compared with surface drip irrigation. Plant growth and leaf production were further enhanced by mulching with cowpea due to improved soil moisture conservation and enhanced soil fertility through biological nitrogen fixation (Ramya *et al.*, 2023) [52].

The effect of irrigation levels on mulberry productivity has also been reported in other studies. Higher leaf yield (9.79-11.19 t ha⁻¹) and crude protein content (19.98-21.19 g 100 g⁻¹) were produced under irrigation at 30 mm, indicating that adequate soil moisture promotes biomass accumulation and improves photosynthetic efficiency (Ren *et al.*, 2025) [57]. In addition, the use of alternative water sources has also been explored in mulberry cultivation. Cocoon yield was increased by 21.87-26% under irrigation with diluted distillery spent wash (33%) due to improved nutrient availability in wastewater, although higher concentrations of industrial effluents were reported to negatively affect soil properties (Kalpana *et al.*, 2018) [28]. Hydrogels integrated with sensor-based irrigation and fertigation have also been reported to improve mulberry growth, water productivity,

nutrient status and silkworm performance. Higher plant height (270.74 cm), shoot length (221.99 cm), number of shoots (28.83 plant⁻¹) and leaves per shoot (42.33) were recorded with the application of starch-based hydrogel @ 6 kg ac⁻¹ under sensor-based irrigation. Maximum leaf area (190.01 cm²) and leaf yield (3.25 kg plant⁻¹ and 6688.66 kg ha⁻¹ crop⁻¹) were also recorded compared with the control (2.55 kg plant⁻¹ and 5246.19 kg ha⁻¹ crop⁻¹). Water productivity was increased to 590.29 kg ha⁻¹ cm with 33.23% irrigation water saving due to the high water-holding capacity of hydrogels, which maintain soil moisture in the rhizosphere and enhance nutrient uptake (Harshita Mala *et al.*, 2023a) [17]. Similarly, shoot length (191.42 cm), shoots per plant (22.73), leaves per shoot (32.44) and leaf area (190.04 cm²) were significantly improved under fertigation with 100% RDNK combined with starch-based hydrogel @ 6 kg ac⁻¹. Higher leaf yield (3.73 kg plant⁻¹ and 8116 kg ha⁻¹) with a 44.11% increase over the control and water productivity of 611.61 kg ha⁻¹ cm were also recorded (Ranganatha *et al.*, 2025). Hydrogel application was also found to improve soil and leaf nutrient status in mulberry. Higher soil nitrogen (282.03 kg ha⁻¹), phosphorus (40.78 kg ha⁻¹) and potassium (231.35 kg ha⁻¹) along with increased secondary and micronutrients were recorded due to reduced nutrient leaching and improved nutrient retention in the root zone (Harshita Mala *et al.*, 2023b) [19]. Similarly, maximum leaf nitrogen (3.25%), phosphorus (0.35%) and potassium (1.85%) were recorded under hydrogel application, indicating improved nutrient uptake under better soil moisture conditions (Harshita Mala *et al.*, 2024a) [18]. Hydrogel combined with 100% RDNK through fertigation was also reported to improve soil nutrient status (N 251.82 kg ha⁻¹, P 37.53 kg ha⁻¹ and K 229.76 kg ha⁻¹) and leaf biochemical parameters such as chlorophyll (2.56 mg g⁻¹) and leaf moisture (75.47%), reflecting enhanced photosynthetic efficiency (Ranganatha *et al.*, 2026a).

Improved mulberry leaf quality under hydrogel and fertigation treatments was also found to enhance silkworm growth and cocoon productivity. Maximum larval weight (46.50 g per 10 larvae), cocoon weight (2.47 g) and filament length (1368.67 m) were recorded when silkworms were fed with leaves from hydrogel-treated plants (Harshita Mala *et al.*, 2024b) [20]. Similarly, higher larval weight (45.73 g per 10 larvae), cocoon yield (23.48 kg per 10,000 larvae) and filament length (1344 m)

were recorded under hydrogel integrated with fertigation. These improvements were mainly attributed to enhanced leaf nutritional quality and moisture content resulting from better soil moisture retention and nutrient availability in the root zone (Ranganatha *et al.*, 2026b).

Physiological Stress Tolerance

An increase in CO₂ concentration from 400 to 800 μmol mol⁻¹ was found to increase the net photosynthetic rate by 26.85% and improve water use efficiency. PSII photochemical efficiency parameters such as Fv/Fm and PIABS were also observed to increase under elevated CO₂ conditions (Liu *et al.*, 2019). These results were attributed to enhanced carbon assimilation and reduced transpiration rates under elevated CO₂ conditions. Drought tolerance mechanisms in mulberry cultivars were also studied to understand physiological and biochemical

responses under water stress. Higher relative water content (74.4%) and water use efficiency were maintained by the cultivar V-1 compared with S-36 and K-2 cultivars. Higher proline accumulation and antioxidant activity were also observed (Guha *et al.*, 2010) [15]. These physiological adaptations were reported to help maintain photosynthesis and cellular stability under drought conditions.

Table 3: Comparative analysis of selected morpho-anatomical parameters in two mulberry cultivars

Morpho-anatomical traits	Victory-1	Kanva-2
Leaf thickness (nm)	11672.6	9374.0
Palisade thickness (nm)	5576.0	3274.7
% palisade tissue/leaf cross-section	4874.5	3575.1
Phloem width of stem (nm)	36074.0	27576.5
Xylem poles/root cross-section	3575.8	2274.7
Root length (μm)	4575.6	2875.0
Root weight (g)	18476.8	142716.6

(Guha *et al.*, 2010) [15]

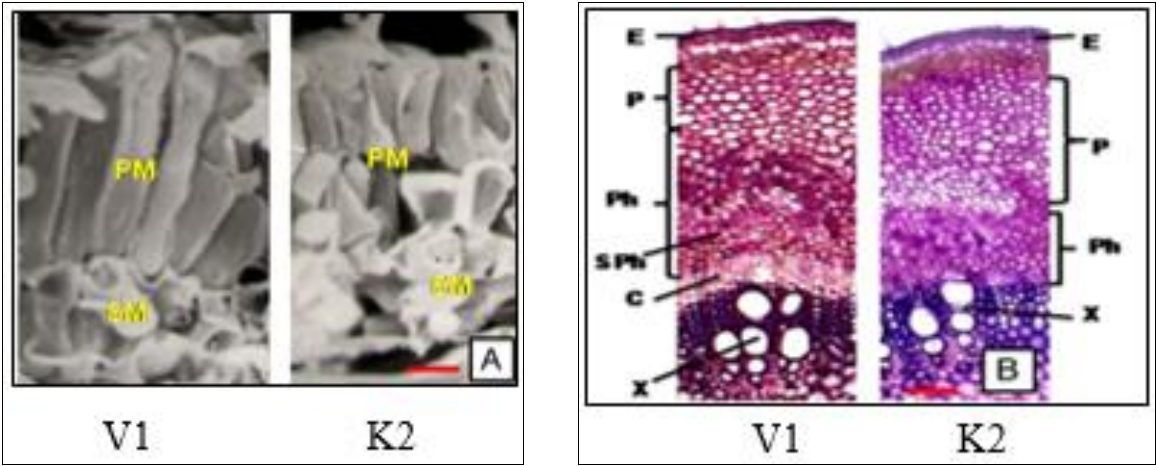


Fig. 2: Variabilities in morpho-anatomical features in V₁ and K₂ mulberry cultivars, (A) scanning electron photomicrographs of leaf cross-sections showing a typical arrangement of palisade mesophyll (PM) and spongy mesophyll (SM) cells, (B) cross-sections through stems of V₁ and K₂ showing different layers of epidermis (E), parenchyma (P), phloem (Ph), secondary phloem (S Ph), cambium (C) and xylem vessels (X) (Guha *et al.*, 2010) [15]

Leaf thickness was found to be significantly greater in V₁ compared to K₂. The height and thickness of palisade cells were also observed to show marked variation between the two genotypes. A palisade thickness of 55 mm was recorded in V₁ leaves, whereas a reduced palisade thickness of 32 mm was observed in K₂ leaves. Moreover, a higher percentage ratio of

the palisade portion of mesophyll was recorded in V₁ (48%) compared with K₂ (35%). The phloem width in the stem of V₁ was observed to be larger (360 mm), with a prominent layer of secondary phloem, whereas in K₂ the phloem width was recorded to be only 275 mm.

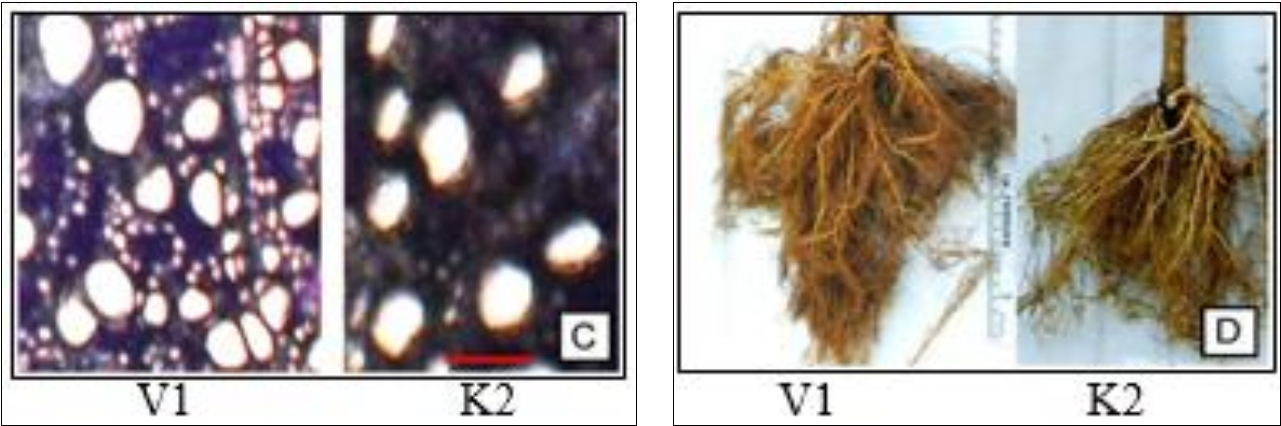


Fig 3: Variabilities in morpho-anatomical features in V₁ and K₂ mulberry cultivars, (C) variation in root xylem density within the cultivars, (D) differences in root morphology showing larger root length and higher density of secondary and tertiary roots in V₁ compared to K₂ (Guha *et al.*, 2010) [15]

Contrasting differences in the number of xylem vessels between the two cultivars were also observed in the transverse section of roots. The maximum number of xylem poles was recorded in V₁. Significant variation was also observed among the genotypes with respect to root length and root weight. Longer root length

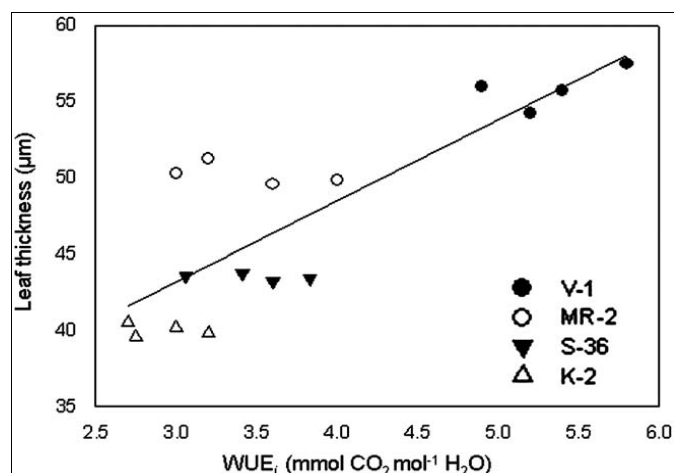


Fig 4: Relationship between leaf thickness and WUE in four mulberry cultivars under drought stress. Each point represents mean of four independent measurements from individual plants (Guha *et al.*, 2010) ^[15]

Innate morphological and anatomical traits, such as thicker leaves resulting from well-developed palisade tissue, were possessed by V₁. These traits were reported to contribute to the maintenance of green leaves under stress conditions and to the retention of higher amounts of photosynthetic pigments. Consequently, reasonably high photosynthetic rates and beneficial water use efficiency were maintained (Guha *et al.*, 2010) ^[15].

Nutrient management in mulberry Fertigation and Fertilizer Optimization

Balanced fertilization and efficient nutrient management have been recognized to play an important role in improving mulberry growth, leaf yield and nutrient use efficiency. Application of N-P₂O₅-K₂O @ 67-36-22 kg ha⁻¹ along with sulphur (8 kg ha⁻¹) and zinc (1 kg ha⁻¹) was found to significantly increase shoot number (12.7 plant⁻¹), leaf number (20.4 plant⁻¹) and shoot

and higher root weight were recorded in V₁ compared with K₂. A greater density of secondary roots with an innumerable entangled mass of tertiary roots (feeder roots) was observed in the root system of V₁ compared to K₂.

length (157.9 cm), resulting in higher leaf yield (11,844 kg ha⁻¹) compared with farmers' practice (9,940 kg ha⁻¹) and fertilizer omission plots (4,675 kg ha⁻¹). Leaf biochemical parameters such as soluble protein (24.5 mg g⁻¹) and soluble sugars (39.0 mg g⁻¹) were also enhanced due to improved chlorophyll formation, photosynthetic efficiency and nutrient uptake (Rajendran *et al.*, 2021) ^[51]. The recommended dose of NPK along with secondary nutrients Ca, Mg and S (82.5:27.5:25 kg ha⁻¹ yr⁻¹) was also reported to improve shoot growth, leaf area (179.30 cm²) and leaf yield (9419.69 kg ha⁻¹ crop⁻¹), highlighting the role of secondary nutrients in photosynthesis and nutrient metabolism (Harish Reddy *et al.*, 2024) ^[67].

Fertilizer scheduling and fertigation techniques have also been shown to enhance nutrient use efficiency and mulberry productivity. Application of 125% recommended dose of fertilizers (84:45:28 kg NPK ha⁻¹ crop⁻¹) in two splits at 15 and 45 days after pruning was reported to record maximum shoot length (142.2 cm), leaves per plant (22.9) and leaf yield (14.07 t ha⁻¹ crop⁻¹) compared with single application of 100% RDF. Nutrient use efficiency was reported to reach 89.6 kg leaf per kg NPK due to continuous nutrient availability in the root zone (Mahesh *et al.*, 2020) ^[34]. Application of 100% NPK through water-soluble fertilizers along with FYM through fertigation was reported to increase shoot height (1.38 m), number of branches (19.33 plant⁻¹) and leaf yield (4.50 t ha⁻¹ crop⁻¹), while improved cocoon traits were recorded with 75% NPK fertigation due to balanced nutrient supply and improved leaf quality (Naveen *et al.*, 2019) ^[41]. Low-cost drip fertigation (LCDF) was also found to significantly improve mulberry productivity, where 100% RDF recorded the maximum leaf yield (7356 kg ha⁻¹). Fertigation with 75% RDF through LCDF was reported to increase leaf yield by 26% and improve leaf quality with maximum total soluble protein (56%) and soluble sugar (28%) compared with the control. Water use was reduced by 24%, resulting in improved water use efficiency (61%) and nutrient use efficiency (63%) (Mahesh *et al.*, 2022) ^[34].

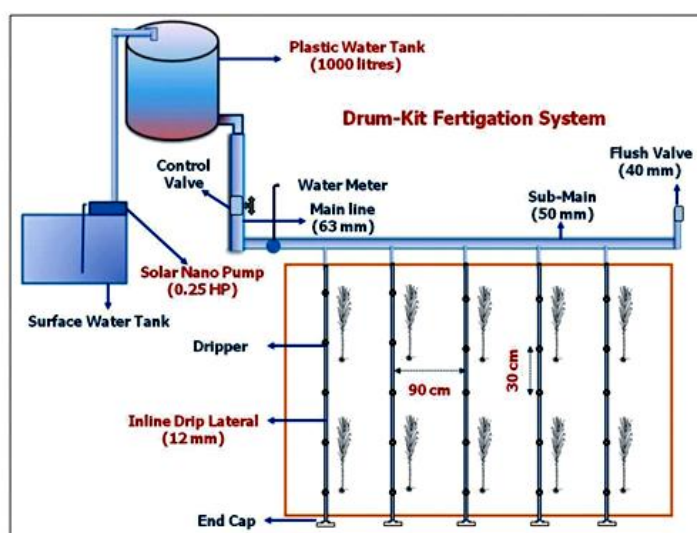
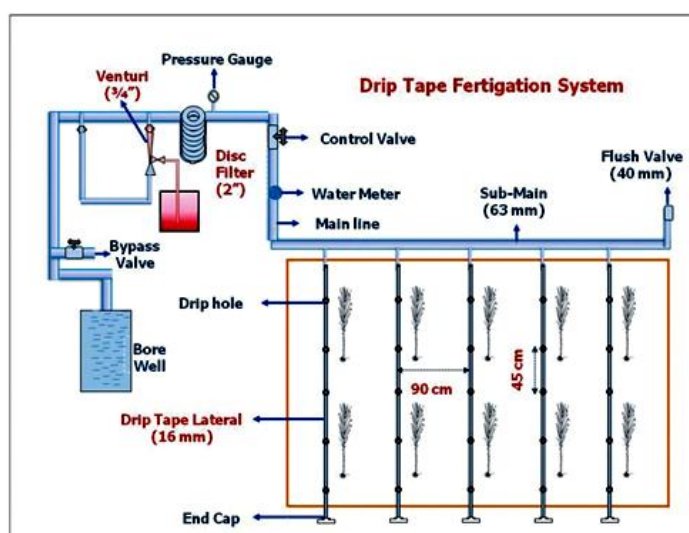


Fig 5: The schematic representation of the DTF and DKF systems.

Integrated fertilizer management practices combining soil and foliar nutrient application have also been found to improve mulberry growth and leaf quality. Basal application of NPK along with foliar spray of urea and liquid fertilizer was reported to increase leaf area (638.64 cm²), shoot length (173.25 cm) and annual leaf yield (41,610 kg ha⁻¹), while leaf moisture (74.38%) and crude protein content (21.01%) were also enhanced due to improved nutrient assimilation and physiological activity (Ahmed *et al.*, 2017) ^[1]. Studies on nutrient dynamics under fertigation further indicated that fertilizer use efficiency is improved through localized nutrient delivery. Higher soil moisture and nutrient concentration within the wetted root zone were maintained through drip fertigation, thereby reducing nutrient losses through leaching and improving nutrient availability for mulberry plants (Arunadevi and Selvaraj, 2013) ^[2]. Environmental factors such as elevated CO₂ have also been reported to influence nutrient use efficiency in mulberry. Total biomass was increased by 16.6-71.6% and net photosynthetic rate was enhanced by 27-30% under elevated CO₂ levels (720-770 ppm), while water use efficiency was improved due to reduced transpiration. Although leaf nutrient concentrations of N, P and K were slightly decreased due to biomass dilution, overall nutrient accumulation and nutrient use efficiency were found to increase, indicating that mulberry productivity could be maintained even with reduced fertilizer inputs under elevated CO₂ conditions (Shi *et al.*, 2026).

Micronutrient Supplementation

Micronutrient fertilization through foliar spray has been reported to significantly improve mulberry growth, leaf yield and cocoon productivity. Shoot length (159.8 cm) and leaf yield (13,935 kg ha⁻¹ harvest⁻¹) were increased through the combined foliar application of ZnSO₄, FeSO₄, boric acid, MnSO₄ and Na₂MoO₄ compared with the control (9,057 kg ha⁻¹). Cocoon yield was also increased to 580 kg ha⁻¹ (Geetha *et al.*, 2017) ^[12]. Similarly, biochemical parameters of mulberry leaves were improved through combined micronutrient spray, with higher chlorophyll content (2.44 mg g⁻¹), crude protein (24.21%) and moisture retention (84.28%) recorded compared with untreated plants (Geetha *et al.*, 2015) ^[11]. Mulberry leaf yield and silkworm performance were also enhanced through multinutrient foliar spray, where higher leaf nitrogen content (3.87%), shoot growth and leaf yield (7.517 kg plant⁻¹) were recorded along with improved cocoon weight (2.60 g) and shell ratio (22.61%) (Mir *et al.*, 2024) ^[39]. These improvements were mainly attributed to the role of micronutrients such as zinc, iron and manganese in chlorophyll synthesis, enzyme activation and nitrogen metabolism, which enhance photosynthetic efficiency and improve the nutritional quality of mulberry leaves.

Soil application of micronutrients has also been reported to enhance mulberry productivity and silk quality. Leaf chlorophyll content (2.813 mg g⁻¹) and filament length (918.22 m) were increased through the combined soil application of FeSO₄, ZnSO₄, MnSO₄, CuSO₄ and borax, thereby improving cocoon quality (Shilpashree *et al.*, 2015) ^[63]. Similarly, leaf yield was increased to 65 t ha⁻¹ year⁻¹ and cocoon weight to 1.92 g through soil application of ZnSO₄ @ 20 kg ha⁻¹ due to the role of zinc in auxin synthesis, protein formation and carbohydrate metabolism (Sowmya and Narayanaswamy, 2016) ^[68]. Combined soil and foliar application of micronutrients was also reported to improve mulberry growth and silkworm performance, with increased leaf yield (6850 kg ha⁻¹) and cocoon yield (76.39 kg per 100 DFLs) (Rajegowda *et al.*, 2022) ^[50]. In addition, silkworm growth efficiency and larval assimilation were enhanced through micronutrient fertilization due to improved mineral composition of mulberry leaves, which supports better digestive enzyme

activity and metabolic efficiency (Marin *et al.*, 2023) ^[36]. These results indicate that micronutrients act as cofactors for several metabolic enzymes, participate in chlorophyll formation and carbohydrate metabolism, and ultimately improve mulberry leaf quality and silk production.

Organic and Integrated Nutrient Management

Organic and integrated nutrient management practices have been reported to improve soil health, mulberry growth and cocoon productivity. Available soil nutrients such as nitrogen (283.73 kg ha⁻¹), phosphorus (35.81 kg ha⁻¹) and potassium (340.12 kg ha⁻¹) were increased under organic farming practices, which resulted in higher leaf yield (55.80 t ha⁻¹ year⁻¹) compared with chemical fertilization (43.41 t ha⁻¹ year⁻¹) (Devi and Sakthivel, 2018) ^[6]. Similarly, biochemical constituents of mulberry leaves were improved through organic-based nutrient management involving vermicompost, biofertilizers and NPK fertilizers, where maximum leaf moisture (76.42%), chlorophyll (1.705 mg g⁻¹), protein (32.27 mg g⁻¹) and sugar content (12.84 mg g⁻¹) were recorded due to gradual nutrient release and improved soil biological activity (Umesha and Sannappa, 2014) ^[71].

Integrated nutrient management practices have also been found to enhance mulberry productivity and soil fertility. Plant height (162.5 cm), leaf yield (6.8-8.6 t acre⁻¹) and cocoon yield (12.87 kg per 10,000 larvae) were increased through the combined application of NPK fertilizers, vermicompost and *Azotobacter* under rainfed conditions. Beneficial microbial populations in the rhizosphere were increased through drip irrigation combined with green manure and biofertilizers, and plant growth parameters such as plant height (189 cm) and leaf number (40 per stem) were also improved. These improvements were mainly attributed to enhanced microbial activity, better nutrient cycling and improved nutrient availability in the root zone, which ultimately enhance mulberry growth and leaf quality for silkworm feeding (Nithya *et al.*, 2011) ^[42].

Improved Genotypes and Soil-Specific Management

Mulberry genotype selection and soil fertility management have been reported to play an important role in improving leaf yield and silkworm productivity, particularly under specific soil conditions. Maximum photosynthetic rate (13.25-13.90 μmol m⁻² s⁻¹), soluble protein content (25.44 mg g⁻¹) and annual leaf yield (24,558 kg ha⁻¹) were recorded in genotype Tr-23 compared with the check variety BC259 due to better nutrient utilization and physiological adaptability under acidic soil conditions (Ghosh *et al.*, 2011) ^[13]. Similarly, mulberry productivity in acidic soils was improved through soil test-based fertilizer recommendations, where leaf yield increased to 9.36-9.80 t ha⁻¹ compared with 8.31-8.77 t ha⁻¹ under farmers' practice due to balanced nutrient application according to soil fertility status.

Crop management practices such as plant spacing and varietal selection have also been reported to influence mulberry growth and silkworm performance. Maximum plant height (286.08 cm) and leaf weight were recorded under optimum spacing (3.0 × 1.0 ft) combined with recommended NPK fertilization due to efficient utilization of nutrients, improved light interception and optimum plant density (Shinde *et al.*, 2012) ^[64]. In addition, improved silkworm performance was observed when silkworms were reared on mulberry varieties with maximum mineral composition. Maximum cocoon weight and filament length were produced when silkworms were fed with Jorhat and TR10 mulberry varieties, which was attributed to the maximum mineral content in these varieties that enhances silk protein synthesis and improves larval growth and cocoon quality (Ruth *et al.*, 2019) ^[59].

Summary

Efficient water and nutrient management is essential for improving mulberry productivity and sustaining sericulture. Studies show that improved irrigation methods such as drip irrigation, subsurface drip irrigation, sensor-based irrigation and hydrogel application enhance water use efficiency by maintaining optimum soil moisture and reducing water losses. Similarly, balanced fertilization, fertigation, micronutrient supplementation and integrated nutrient management improve nutrient uptake, leaf quality and yield. Organic inputs and biofertilizers further enhance soil fertility and microbial activity. Overall, integrating advanced irrigation techniques with efficient nutrient management practices significantly improves mulberry growth, leaf productivity and cocoon yield while promoting sustainable sericulture production.

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