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Drip irrigation on productivity, water use efficiency and profitability of turmeric (*Curcuma longa*) grown under mulched and non-mulched conditions

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ABSTRACT

Turmeric cultivation primarily thrives in India, with significant presence in Bangladesh, Thailand, Cambodia, China, Indonesia, Philippines, and Malaysia. India leads globally in both area (0.19 Mha) and production (0.844 MT) of turmeric. Despite this, there's a recognized gap in research regarding the combined effects of mulching and drip fertigation on turmeric growth in Tamil Nadu conditions. Therefore, this study aims to assess how mulching and drip fertigation impact water usage, turmeric growth, productivity, and post-harvest soil health via field experiments. The treatments comprise of different mulching techniques (M1-25 μm Plastic Mulching, M2-50 μm Plastic Mulching, M3- Organic Mulching, M4-No Mulching) as the main plot, coupled with various irrigation regimes as the sub plot (S1-100% of pan evaporation, S2- 80% of pan evaporation, S3- 60% of pan evaporation), in a split plot design. Findings show that 50-μm Plastic Mulching (M2) notably enhances turmeric growth parameters, including plant height, biomass, leaf count, and yield attributes such as tillers and rhizomes, compared to no mulch. Significantly, when 80% of pan evaporation is utilized in drip irrigation, it showcases the most pronounced plant growth and yield characteristics, with plastic mulch at this level significantly improving water and nutrient use efficiency while increasing beneficial compounds like Curcumin and oleoresin. The highest fresh rhizome yield is observed with 50-μm plastic mulch and 80% pan evaporation (M2S2), displaying a 39.79% increase compared to the control. Additionally, the study notes effects on microbial populations and mulch degradation. Economically, M2S2 exhibits the highest profitability with a benefit-cost ratio of 3.23 compared to other treatments. Implementing these practices not only enhances yields but also conserves water (estimated at 9.15 mm^3) while emphasizing the importance of drip irrigation, fertilizer application, and mulching in boosting turmeric productivity, optimizing resource efficiency, and ensuring economic and environmental sustainability.

1. Introduction

Turmeric, scientifically known as *Curcuma longa* L., is a member of the Zingiberaceae family and originates from South-East Asia ([1];). Revered in Hindu mythology, and called as "golden spice of India" and has been utilized from time immemorial in medicinal, cosmetic, and culinary applications [2,3]. Its versatile use spans across medicine, cosmetics, food, and spice industries, with its dye finding application in various cosmetic and pharmaceutical products. Studies suggest its efficacy in various medical conditions, attributing to its antiseptic, anti-cancerous, anti-inflammatory, and antibacterial properties [4–8]. Turmeric typically contains 1.8–5.4% curcumin content, 2.5–7.2% turmerol or essential oil, 69.4% carbohydrates, 5% fat, and 3.0% minerals. The yellow color of turmeric is attributed to a mixture of curcuminoides

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and curcumin [9,10].

Turmeric is grown in India, followed by Bangladesh, Cambodia, China, Thailand, Malaysia, Philippines and Indonesia. India stands first in world [11] with respect to area (0.19 Mha) and production (0.844 MT). In India, it is cultivated in the following states viz., Andhra Pradesh, Tamil Nadu, Maharashtra, Kerala, Orissa, West Bengal, Karnataka and some of the North Eastern states [12]. In some of the areas it is cultivated as intercrop with widely spaced crops such as pulses, horticultural crops and other perennial crops, since it will grow well under shaded conditions. Turmeric is a highly valued crop in India, with Tamil Nadu being one of the major producers. It holds significant economic importance for farmers in the region due to its high market demand both domestically and internationally. Tamil Nadu farmers grow turmeric since it is having large economic significance, climatic suitability, cultural importance, potential for crop diversification, and health benefits. Usually in Tamil Nadu, it is planted during summer months (especially May) and harvested by January, which necessitates high water requirement. In addition, being a long duration crop, evaporative demand is also high. Mulching is a management strategy of covering the topsoil to reduce soil evaporation and it is a good agricultural practice (GAP) for turmeric since it will help in conserving the moisture. Besides, it increases the temperature of soil, which aids in proper germination of the rhizome, improves the soil physico chemical properties and arrests the weed growth etc. Besides, it averts erosion of soil and nutrient loss during heavy rains [13,14]. In addition, mulching will help to decrease in the incidence of insect pests, improvement in crop productivity and improving the utilization of nutrients (nutrient use efficiency) applied to the soil. In general, soils under mulching remains structurally not compact, with good aeration, which helps the roots to acquire enough oxygen and enhances the microbes [15]. Mulching with plastic will not allow the carbon dioxide (CO_2), to evolve from the soil, and CO_2 gas is primarily important for plant metabolic activities or photosynthesis. Hence, higher levels of CO_2 gas will be there under the mulching, and it will come through the holes in which plants are planted. This will result in higher concentration of CO_2 gas, which will help the plants to utilize this elevated CO_2 and helps in improving the photosynthesis, resulting in higher yield and this increase in CO_2 gas effect is known as "chimney effect" [16].

Among the agronomic practices, application of water and nutrients are the most significant factors i.e., it can be controlled by irrigation scheduling and fertilizer application and mulching may strongly influence the retention characteristics of water in the soil and in turn helps the plant to absorb the moisture and nutrients [17,18]. In the case of turmeric, mulching decreases loss of water through evaporation, contain the growth of weeds, adjust temperature of the soil and prevent the rhizomes from drying (desiccation) in germination phase, since it is usually planted in summer [19,20]. As stated earlier, mulching by using straw resulted in encouraging outcome on growth parameters and productivity in many of the crops and it was due to the rapid emergence, quick growth of crop, since no weed competition as compared with non-mulching [21]. In arid regions, mulching also results in reducing the speed of the wind at the soil surface reduces and strongly influences the soil moisture, water retention characteristics of soil and micro flora and fauna in soil [22,23]. In addition, it conserves the soil from high intensity rainfall associated splash erosion and also improves the water infiltration rate in to the soil by obstructing the runoff associated with heavy rains [24]. Turmeric growing period is 9–10 months long duration and hence it requires large quantity of water, which requires assured water supply throughout its entire growth cycle [25]. Usually, irrigation interval for turmeric crop is 5–7 days and it mostly depends on soil and weather factors of the location. Water scarcity is being encountered across the globe and this holds good for turmeric growing regions also, which makes us to think about other options to reduce the irrigation water used. Out of several options, deficit irrigation is a viable option to minimize use of water and producing more crop per drop of water used. However, this should be done without compromising on the crop production (yield). This can be attained by use of advanced technologies such as micro irrigation methods over traditional practices [26,27]. Drip irrigation is one of the advanced techniques for scientific water management since this will improve the crop yield and WUE of field crops [28]. It is a very proficient method of applying water to plant at their root zone and which results in increasing the WUE (water use efficiency) and crop productivity [29]. Since the water is applied in very small quantities near to root zone, this will minimize the water that leaches beyond the active plant root zone [30]. In general, these efficient drip methods of irrigation reduce evaporation, surface runoff, leaching, deep percolation and growth of weeds [31].

Many of the studies reported saving of water to the tune of (12%–84%) apart from improvement in crop yield in different crops [32]. In a nutshell, if we look at the advantages of drip irrigation, it improves the WUE, NUE, crop and water productivity and reduction in weed growth, usage of labor and ultimately economic profitability in many crops. In addition to application of water, water soluble fertilizers (WSF) as nutrients required to the plants in exact quantities are also can be applied and at more frequencies depending on the need of the plant ([28,33,34]). Application of WSF as nutrients through drip fertigation has been found to dramatically improve the quality of many horticultural crops [35]. Application of water-soluble fertilizers in small and precise quantities as per the plant requirement in its root zone will result in greater use efficiency of applied nutrients because of proper uptake and no other losses [36]. However, care should be taken to apply the right quantity of nutrients at right frequency depending on the growth stages of the crop [37,38]. Application of all essential nutrients in a balanced manner is essential in any crop management, by considering the soil moisture status. Varied response of the fertigation and mulching on different crops (genotypes) exists and this is due to the crop specific genetic potential and hence this needs to be studied to understand the same especially in the semi-arid region of Tamil Nadu, where turmeric is significantly important crop [39].

The in-depth literature review showed that there is no systematic study on the synergistic impact of mulching and drip fertigation in turmeric under Tamil Nadu conditions. By considering this, this study was carried out to assess the impact of mulching and drip fertigation on the WUE, turmeric growth and productivity and its impact on post-harvest soil health. The uniqueness and novelty of the study lie in its specific focus on turmeric under semi-arid regions, its examination of drip irrigation under mulched and non-mulched conditions, its holistic approach to sustainability, and its potential to generate actionable insights for improving water use efficiency, productivity, and profitability in turmeric cultivation.

2. Materials and methods

2.1. Study area

Data on turmeric area for Tamil Nadu State showed that total cultivated area was 35,795 ha and it was dominant in the following districts, viz., Erode, Dharmapuri, Salem, Namakkal, Villupuram and Coimbatore (www.indianspices.com) (Fig. 1). The field experiment was carried out at Agricultural Research Station (ARS), Bhavanisagar, Western Part of Tamil Nadu, in South India and this station is positioned in Lower Bhavani Irrigation project and it is a vital agricultural research center that region (Fig. 1). It is located at 11°29′ N and 77°80′ E with an altitude of 256 m above MSL. The area is under semiarid climate, in which March to May will be summer with high temperature and dry climate. Rainfall is bimodal, i.e. it receives rainfall in both Northeast and South West monsoon. The average temperature for both maximum and minimum usually shows larger variations depending upon the seasons (summer and winter). The maximum temperature exceeds 35 °C during summer. The average annual rainfall ranges between 500 and 700 mm, and 70% of this is contributed from Northeast monsoon (October–December) and remaining 30% in South West monsoon (June–September)

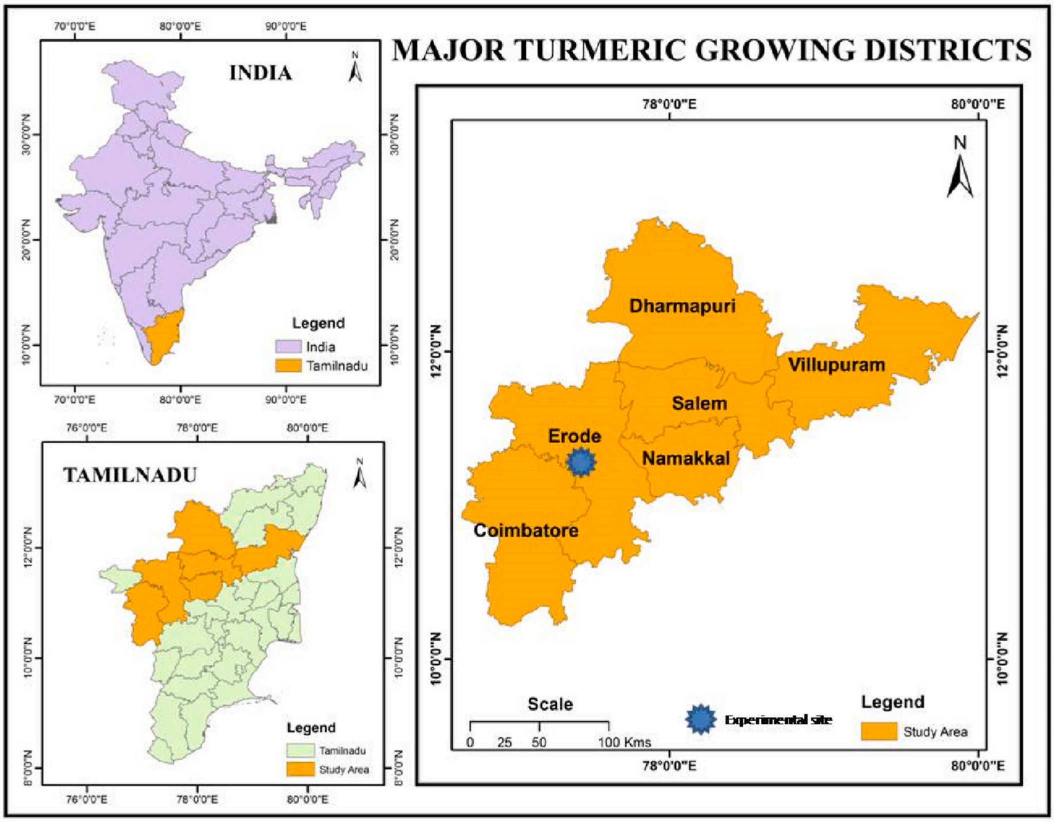


Fig. 1. Major turmeric growing areas of Tamil Nadu.

season.

The meteorology data was recorded at ARS, Bhavanisagar, for the period of experiment is presented in Fig. 2. Rain fall received during the two seasons was 651.1 and 737.0 mm, respectively. The average maximum and minimum temperature recorded was 36.6 °C and 18.7 °C respectively during the growing seasons.

2.2. Soils and methodology

Experimental field soils are having sandy loam texture with 59.0% sand, 18.4% clay and 22.6% silt. Other physical properties such as water holding capacity, Bulk density and infiltration rate was 14.9%, 1.44 g cm^{-3} and 10 mm h^{-1}, respectively. The experimental field is divided in to plots and within the plot beds of equal size of 1 m × 6 m was taken and each bed represented a single treatment replication. Spacing adopted for Turmeric (var. BSR-1) was 0.3 m × 0.5 m (plant vs row) and it was

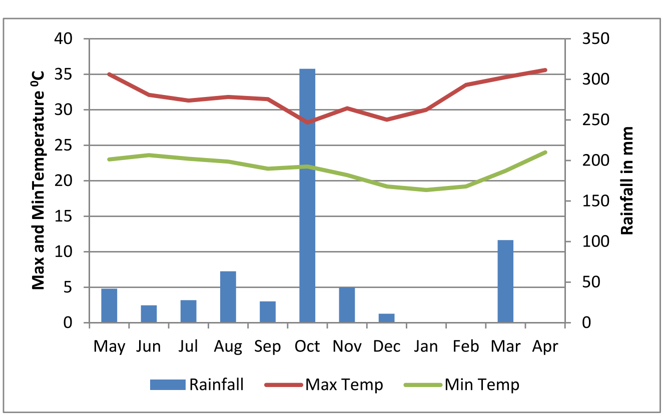


Fig. 2. Weather Parameters observed during the Experiment period.

planted as two rows on each bed. To arrest the soil moisture movement between beds, 0.5 m gap was left in between beds. The design adopted was split plot with seven treatments and three replications. The various treatments were as follows in main plot: M_1- 25 μm plastic mulching (50 gauge), M_2- 50 μm plastic mulching (100 gauge), M_3- organic mulching (crop waste), M_4-no mulching (control) used as a treatment of mulch materials. The sub plot consists of S_1- 100% of pan evaporation, S_2- 80% of pan evaporation, S_3-60% of pan evaporation. The main and sub plots were randomized in the available blocks and split plot design was adopted with seven treatments and three replications. Fig. 3 shows the imposition of treatments along with the comprehensive layout of the experimental plot. Required moisture as per the treatments was supplied through drip irrigation system and irrigation was scheduled and controlled by separate valve according to the treatments. The drip laterals are having inline drippers with 4 lph emission capacity, with a spacing of 30 cm between drippers and each dripper will give water to four plants and each drip lateral will serve two rows. The black polyethylene film mulching of 100 and 50 gauge (50 and 25 μ) thickness and in addition to cover 100% of bed area and interspace, residues of crops (Biodegradable organic mulching materials were used – such as paddy straw, maize straw and sorghum straw apart from starch mixed with biodegradable polyesters) were used as mulching materials. All other agronomic management activities viz., fertigation, plant protection, covering up of soil, foliar spray was followed as per the Horticulture Guide, 2004.

2.3. Irrigation scheduling

Irrigation scheduling was based on the ratio of irrigation water used (IW) to cumulative pan evaporation (CPE), denoted as IW/CPE. Three different IW/CPE ratios of 0.6, 0.8, and 1.0 were tested in the experiment, and the quantum of water used was approximately 22 mm, 30 mm, and 38 mm of net irrigation water depth. The quantity of water

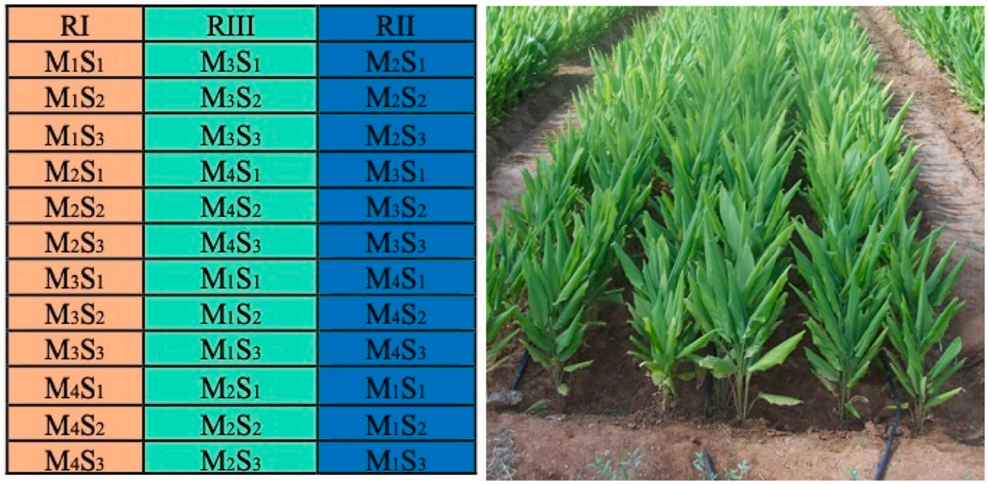


Fig. 3. Schematic layout of the Turmeric trial with a field photo.

applied was calculated from CPE but cross-checked against crop water requirements using the FAO CROPWAT Model [40]. Although the irrigation interval remained constant, the amount of irrigation water applied varied, with the timing of irrigation increasing proportionately from 0.6 to 1.0 based on the IW/CPE ratio. In the case of drip irrigation efficiency was considered as 90 % and in the case of surface irrigation, it was considered as 50% respectively, by accounting conveyance and other losses [34,41]. Notably, in the semi-arid agro-climatic conditions of Tamil Nadu, the study quantifies that irrigating 1 ha of turmeric crop requires a total of 1276.8 mm of water with the drip irrigation system.

2.4. Fertilizer schedule and quality

For turmeric the recommended doses of fertilizers (RDF) are 150 kg of N (nitrogen), 60 kg of P (Phosphorus) and 108 kg of K (potassium) ha^{-1}. Out of this N and K were provided as Urea and Muriate of potash (MoP) through drip fertigation, whereas entire quantity of Phosphorus (P) was applied through SSP (single super phosphate) at the time of planting (basal) after the last ploughing. Organic manure (FYM) @ 10 t ha^{-1} was given before planting. The quantities of fertilizer applied are furnished in Table 1. The fertigation schedule was in the interval of 7 days to meet the requirement of crop. The detailed fertigation schedules are presented in Supplementary Table S1. The various observations on morphological characters, yield attributes, quality parameters and crop productivity were observed at crop growth stages using standard procedures.

2.5. Soil sample analysis

To assess the influence of mulching, irrigation and drip fertigation, soil samples of all the individual treatments were collected according to the standard procedure. To explain further, 10 replicated soil samples were collected from the beds, and using quartering method, a composite sample was taken per treatment. Soil analysis was carried out for its physico-chemical characteristic parameters. In addition, soil temperature was also measured at different depths of soil viz., 15, 30 and 90 cm. Experimental field soils were sandy loam in texture and as per USDA taxonomic classification it is *Typic Ustropept*. The soil pH was neutral (7.8), organic carbon is low (0.34) and with respect to NPK, it is low in the case of N (229 kg ha^{-1}) and P (10.1 kg ha^{-1}), whereas it is high in K (179 kg ha^{-1}). In general, there was little variation in the soil properties between various treatment plots at the initial stage/before planting [28,33,42,43]. Field capacity and permanent wilting point of the soils were 21.8 and 10.8 per cent respectively. Similarly, important water quality parameters were also assessed, and pH was 7.2, EC was 1.1 dS m^{-1} respectively.

Similarly, the organic carbon, nitrogen, phosphorous, and potassium contents of the post-harvest soil samples from each treatment were also carried out as per the standard procedures. Subbiah and Asija [44] proposed a system for estimating available soil nitrogen, and the nitrogen content was reported in kg ha^{-1}. Olsen et al. [45] used a calorimeter to assess available soil phosphorus, which was given in kg ha^{-1}. The available potassium was calculated using the Stanford and English [46] 1 N ammonium acetate method and given in kg ha^{-1}.

Table 1
Amount of fertilizer applied for Turmeric.

Name of the Fertilizers	Quantity (kg/ha)
SSP	281
19-19-19	33
13-00-45	65
12-61-00	15
00-00-50	145
Urea	213

Recommended fertilizer dose 150-60-108 kg ha^{-1}
Water soluble fertilizer application 150-150-108 kg ha^{-1}

2.6. Moisture content of the soil

A gravimetric approach was used to assess the soil moisture obtained at different days after planting (15, 30, 60, and 90). The soil sample was placed in a moisture tin (aluminum container), weighed wet, oven dried, then weighed again after drying at 105 °C. The following formula was used to calculate the soil moisture content:

$$\text{Gravimetric water content } (\%) = \frac{\textit{Weight of soil wet} - \textit{Weight of soil} - \textit{dry}}{\textit{Weight of soil} - \textit{dry}} \times 100 \quad (1)$$

2.7. Water and nutrient use efficiency (WUE, NUE)

Water Use Efficiency (WUE) was calculated as the quantity of water required (m^3) to produce the turmeric yield as per equation (2) and the turmeric produced from each harvest was quantified (kg ha^{-1}). The total quantity of water applied during every irrigation was computed and the effective rainfall during the experimental period was deducted in the water balance calculations and total quantity of water used for the experiment was computed. Similarly, NUE was calculated based on the ratio of quantity of nitrogen applied in each treatment to that of total turmeric yield in the same treatment and this is explained in equation (3).

$$WUE = \frac{Turmeric\ yield\ in\ each\ treatment}{Quantity\ of\ water\ used\ in\ each\ treatment}\ \left(\mathrm{kg\ ha^{-1} m^{3}}\right) \quad (2)$$

$$NUE = \frac{Turmeric\ yield\ in\ each\ treatment}{Total\ nitrogen\ used\ in\ each\ treatment} \quad (3)$$

2.8. Enumerating microbial population and biodegradation of mulching materials under field conditions

Mulching's effect on microbial populations (bacteria, actinomycetes and fungus), was studied at three different stages of growth such as initial, fruiting and at harvest. Microbial population was estimated using serial dilution technique and the pour plate method [47] for the composite soil samples. The plates were kept under incubation at 32 2 °C and then the microbial population were counted (2, 5, and 7 days after inoculation), and expressed as cfu per gram of soil, respectively Biodegradation of mulching materials were assessed as follows, Rhizophora sp. and or Avicennia sp., colonized cups were kept in a depth of 5 cm in the soil and the mulching sheets were permitted to naturally degrade in the soil and samples were taken at regular intervals (2, 4, 6 and 9 months) using sterile forceps and then transported to laboratory aseptically. The collected samples were washed thoroughly, and then weighed after shade drying for final weight. The degradation was determined in terms of per cent of weight loss of the materials over a period.

2.9. Crop biometrics and quality parameters

Plant biometrics such as height of plant, number of leaves, leaf length and width, dry matter production and production attributes such as number of tillers, number of primary rhizomes etc were counted using standard procedures. Similarly weed population were also counted from the plot. Curcumin content of the turmeric extract was determined by ASTA [48]. Solvent extraction of turmeric oleoresin was carried out by the method suggested by Indian Standards [49].

2.10. Economic analysis

Economic analysis was calculated for all individual treatments by accounting the cost involved during the cultivation and total (gross) return. Profitability or Benefit Cost ratio (B: C ratio) per Euro spent was calculated as per equation (3).

$$BC = \frac{Total\ (gross)\ return\ \left(Rs.ha^{-1}\right)}{Total\ Cost\ of\ cultivation\ \left(Rs.ha^{-1}\right)} \quad (4)$$

2.11. Simulated water saving for the entire state

Data on turmeric area for the State of Tamil Nadu state as a whole and also based on the districts were turmeric is grown in larger areas were used (www.spicesboard.com) for simulating the water saving, if we adopt drip fertigation technology for the entire cultivated area.

2.12. Statistical analysis

Data collected from both the experiments were analyzed using the appropriate statistical tools and mainly Fischer's method of ANOVA (analysis of variance) technique were used [50]. For weed population analysis, the data on weeds were transformed using the log x + 2 method, as described by Bartlett [51]. This was tested with level of significance test used in "F" and "t" test with $P = 0.05$. To understand, which treatment is significantly better, the average values of irrigation, mulching and their interaction plots values were assessed using Duncan Multiple Range Test (DMRT).

3. Results and discussion

3.1. Soil temperature

Results showed that soil temperature varied with different depths (15, 30, and 90 cm) for black polyethylene mulching and control (Table 2). The mean soil temperature at 15 cm depth ranges from 15.5 °C to 32.4 °C under control plot whereas it varied between 17.0 and 33.4 °C under mulching treatment in winter seasons. During the months of March to May (summer season), mean temperatures at various depths noticed in the range of 17.2–33.4 °C in the control plot and 17.6–34.1 °C in the mulched plot. So, these data confirmed that there is an increase in the soil temperature under mulching and this is mostly due to the evaporation is used to prevent latent heat loss. It is also confirmed that the increase in soil temperature depends on several factors such as color of the mulching materials used, intensity of solar radiation, humidity, ambient temperature, and soil types.

3.2. Drip fertigation and mulch on growth and yield of turmeric crop

Results revealed that the plastic mulch (50μ) significantly influences the plant height (154.33 cm), dry matter production (DMP) (241.95), no. of leaves per plant (14.42), leaf length (60.87 cm), leaf breath (15.78 cm) compared with control (no mulch) (Table 3). This might be due to favorable moisture and temperature condition of the turmeric crop under mulching than the non-mulched conditions [52,53]. In subplot different irrigation levels influences the growth parameters (Table 5). Drip irrigation at 80% of pan evaporation recorded higher growth attributes viz., Plant height (154.50 cm), dry matter production (DMP) (241.09), no. of leaves per plant (14.31), leaf length (60.19 cm), leaf breath (15.46 cm) compared with 60% pan evaporation through drip. The results showed that drip irrigation with 80 % retained the optimal soil moisture regime for turmeric, allowing for improved nutrient uptake. Madhumathi et al. [54] reported that plant growth is higher under better water levels because of the prompt cell wall development and retains the greenness in the crop indicates a lot of photosynthetic activity and nutrient transfer as demonstrated by the leaf greenness.

3.3. Yield attributes

Drip fertigation along with polyethylene mulching has significantly influenced the yield attributes of turmeric (Table 4). Application of plastic mulch (50μ) resulted in significantly higher yield attributes. It reported higher number of tillers, primary and secondary rhizomes per plant and was statistically significant over control and other treatments. Results indicated that mulching treatment resulted in encouraging micro climatic conditions near the root zone of the plant and this is due to the prevention of soil evaporation and conserving the soil moisture thereby maintaining the optimum soil temperature and moisture near the root zone [55]. Increase in soil temperature under polyethylene mulching might have resulted in increased activity of microorganisms which transforms nutrients and made it available to the plants there boosting the yield to higher level in turmeric. Soil covered with polyethylene mulching enhances the accretion of more organic matter (OM) and Humic acid (HA), since run off of fine soil rich in OM and HA during erosion is arrested and this OM and HA are the enriched with plant nutrients that improves the crop growth parameters, yield attributes and higher production [56].

80% pan evaporation through drip irrigation treatment resulted in significantly higher yield attributes than the control and rest of the treatments (Table 6). Drip irrigation recorded higher number of tillers per plant (2.91), number of mother rhizomes (3.31), number of primary rhizomes (10.58) and number of secondary rhizomes (16.62) whereas,

Table 2
Variation in temperature in plastic mulch and control plots at various soil depths.

	Controlling the temperature of the soil (°C)			Temperature of the soil in plastic mulch (°C)		
Season	15 cm	30 cm	90 cm	15 cm	30 cm	90 cm
Winter (Dec–Feb)	15.5–29.5	16.5–31.0	18.5–32.4	17.0–32.1	18.4–32.2	17.4–33.4
Summer (Mar–May)	17.2–30.8	18.1–31.4	19.1–33.4	17.6–34.6	18.8–32.8	19.8–34.1

Table 3
Influence of irrigation through drip system and different mulch on growth parameters of Turmeric.

Treatments	Plant height (cm)	DMP (g/plant)	No. of leaves/plant	Leaf length (cm)	Leaf breath (cm)
Main plot					
M_1	150.33	235.10	13.63	57.10	14.42
M_2	154.33	241.95	14.42	60.87	15.78
M_3	146.00	229.99	13.45	56.02	14.18
M_4	141.33	224.73	13.19	54.70	14.00
SE.D	*2.51*	*3.92*	*0.265*	*1.25*	*0.456*
CD(P = 0.05)	*6.13*	*9.59*	*0.649*	*3.05*	*1.11*
Sub plot					
S_1	151.50	236.98	13.74	57.44	14.45
S_2	154.50	241.09	14.31	60.19	15.46
S_3	138.00	220.77	12.96	53.89	13.88
SE.D	*2.26*	*3.51*	*0.238*	*1.13*	*0.404*
CD(P = 0.05)	*4.78*	*7.44*	*0.504*	*2.39*	*0.856*

M_1- 25 µm Plastic Mulching S_1- 100 % of pan evaporation.
M_2- 50 µm Plastic Mulching S_2- 80% of pan evaporation.
M_3. Organic Mulching S_3- 60% of pan evaporation.
M_4- No Mulching.

Table 4
Influence of drip fertigation system and different mulch on yield attributes and yield of Turmeric.

Treatments	Number of tillers/plant	Number. of mother rhizome/plant	Number of primary rhizome/plant	Number of secondary rhizome/plant
Main plot				
M_1	3.78	2.94	9.39	15.30
M_2	4.19	3.38	11.12	16.67
M_3	3.62	2.72	8.57	14.14
M_4	3.46	2.54	7.91	12.95
SE.D	*0.084*	*0.110*	*0.318*	*0.427*
CD(P = 0.05)	*0.205*	*0.269*	*0.778*	*1.046*
Sub plot				
S_1	2.78	3.06	9.79	15.54
S_2	2.91	3.31	10.58	16.62
S_3	2.37	2.33	7.37	12.14
SE.D	*0.071*	*0.095*	*0.268*	*0.367*
CD(P = 0.05)	*0.151*	*0.201*	*0.568*	*0.778*

M_1- 25 µm Plastic Mulching S_1- 100 % of pan evaporation.
M_2- 50 µm Plastic Mulching S_2- 80% of pan evaporation.
M_3. Organic Mulching S_3- 60% of pan evaporation.
M_4- No Mulching.

corresponding lower yield attributes was recorded in 60% pan evaporation. Irrigation via drip compared to other irrigation systems, at 80 % of pan evaporation might have promoted greater rhizome development because of higher availability nutrients to the turmeric plants, resulting in an increase in both volume and weight of turmeric rhizomes [57,58]

3.4. Weed population

Polyethylene mulching significantly influenced the weed population when compared with the control as presented in Table 5. Weed population per m^2 was 85–100% lower in polyethylene mulching plots as compared with no mulching plot (control) at different stages of crop growth. Mulching controlled the weeds by delaying the emergence of weeds from seeds in the initial stages and in later stage because of the competition from turmeric and its shading effects it will reduce the photosynthesis activity of weeds. In general, the mulching provides the favorable edaphic conditions for turmeric growth and restricts the crop weed competition by providing an upper hand to the crop of interest i.e., turmeric rather than weeds. In one of the earlier studies by Ref. [59], it was reported that population of weeds and dry matter production were less and statistically significant @ 6.25 t/ha mulching than the control. In another study, application of paddy straw (crop residue) as mulching improved the turmeric yield in the range of 59.5–218% as compared with no mulch (control), and that is due reduction in weed population and higher soil moisture retention through prevention of soil evaporation [60]. With respect to irrigation levels also significant difference was noticed in weed population (Table 7). The weed population was found to

Table 5
Influence of different levels of drip irrigation system and crop mulch on weed population, Curcumin content and Oleracin content in Turmeric.

Treatments	Weed population/m^2	Curcumin content %	Oleracin content %
Main plot			
M_1	0.984	4.060	9.147
M_2	–	4.160	9.287
M_3	1.317	3.907	8.970
M_4	1.642	3.873	8.845
SE.D	*0.114*	*0.0096*	*0.0222*
CD(P = 0.05)	*0.278*	*0.0236*	*0.0542*
Sub plot			
S_1	1.072	3.893	9.030
S_2	0.936	3.927	9.217
S_3	1.141	3.683	8.693
SE.D	*0.030*	*0.0390*	*0.0292*
CD(P = 0.05)	*0.062*	*0.0781*	*0.0580*

M_1- 25 µm Plastic Mulching S_1- 100 % of pan evaporation.
M_2- 50 µm Plastic Mulching S_2- 80% of pan evaporation.
M_3. Organic Mulching S_3- 60% of pan evaporation.
M_4- No Mulching.

Table 6
Drip irrigation system and crop mulching on Yield of Turmeric (kg/ha).

Treatments	S_1	S_2	S_3	Mean
M_1	37,880	39,060	31,600	36,180
M_2	41,226	47,988	33,960	41,058
M_3	34,800	35,680	30,800	33,760
M_4	32,450	33,750	28,889	31,696
Mean	36,589	39,120	31,312	
Interaction	*SE.D*		*CD(P = 0.05)*	
M	1205.62		2950.18	
S	1141.59		2420.09	
M*S	2220.09		4920.59	
S*M	2283.18		4840.19	

M_1- 25-µm Plastic Mulching S_1- 100 % of pan evaporation.
M_2- 50-µm Plastic Mulching S_2- 80% of pan evaporation.
M_3. Organic Mulching S_3- 60% of pan evaporation.
M_4- No Mulching.

Table 7
Drip irrigation system and crop mulch on post-harvest nutrient status of turmeric (kg ha^{-1}) soils at 240 DAS.

Treatments	N	P	K
Main plot			
M_1	261	25	221
M_2	252	21	208
M_3	245	18	203
M_4	236	13	186
SE.D	*9.54*	*0.88*	*9.05*
CD(P = 0.05)	*21.08*	*1.96*	*18.82*
Sub plot			
S_1	241	14	192
S_2	262	23	218
S_3	254	19	205
SE.D	*9.28*	*0.94*	*8.96*
CD(P = 0.05)	*20.51*	*2.05*	*18.64*

M_1- 25 µm Plastic Mulching S_1- 100 % of pan evaporation.
M_2- 50 µm Plastic Mulching S_2- 80% of pan evaporation.
M_3- Organic Mulching S_3- 60% of pan evaporation.
M_4- No Mulching.

be less with the drip irrigation (80% and 60% of pan evaporation). This could be because drip irrigation has a good effect for maintaining the soil moisture near the plant root zone, which minimizes soil evaporation and inhibits growth of weeds.

3.5. Quality parameters

Quality parameters such asa curcumin and oleoresin content was significantly influenced by the treatments. The use of 50-µm plastic mulch material resulted in 4.160 and 9.287 percent increase in curcumin and oleoresin content, respectively. Different irrigation levels also influenced the quality parameters (Table 7). The turmeric crop with 80% of pan evaporation through drip produced significantly higher curcumin and oleoresin content % than other irrigation levels. This might be due to favorable temperature and moisture retention conditions and conserve nutrients. This could have happened because the turmeric was given the proper amount of water and nutrients by drip fertigation.

3.6. Yield

Use of different mulching materials resulted in yield improvement in turmeric, and which is evident from Tables 6 and it was statistically also significant. In a two-year study, plastic mulching had a significant impact on turmeric rhizome yield than the control. The maximum fresh rhizome yield of 41,058 $kgha^{-1}$ was recorded in plastic mulch (50µ) and it was significantly higher when compared with no mulching control (31,696 $kgha^{-1}$). The possible reasons are proper germination, soil moisture retention, better weeds control, increased water and nutrient use efficiency as compared with control [56]. This resulted in 22.8% higher yield of turmeric under mulching than the control. Grossman [61] also found higher germination under mulching and plant population was uniform, which is in line with the current study. Mulches also aided in greater decomposition and assist in mineralizing the soil nutrients which enhances the nutrient availability, and increase the yield parameters to the benefit of rhizome output.

Similar to mulching, irrigation treatments also significantly influenced the yield, and the data is shown in Table 8. Maximum turmeric rhizome yield (39,120 kg ha^{-1}) was observed in 80% of pan evaporation through drip irrigation system as compared with rest of the irrigation levels. The results revealed that this treatment showed an increase of 19.96% rhizome yield over the 60% PE, but yield reduced by 6.46% when irrigation was increased to 100% PE. Reason for low yield under 60 % PE might be due to the low soil moisture during the critical growth stages of the crop (water stress) coupled with low availability of plant essential nutrients [62–65]. In general, under drip irrigation along with fertigation system, yield will be higher, since under this system water and nutrients are given in very low rate and more frequently in proximity to the root zone, thereby improving the use efficiency of water and nutrients by preventing other losses. Because water and nutrients are easily available at the root zone, plants are less stressed and hence accelerate photosynthetic to storage organ translocation, resulting in increased output [66]. Venkatesha and Siddalingayya [67] revealed that relatively higher soil moisture and nutrient absorption resulted in higher growth parameters as evidenced by higher plant height, leaf area and chlorophyll content at peak growth stage and total dry matter at maturity might helped for increasing the turmeric yield attributes.

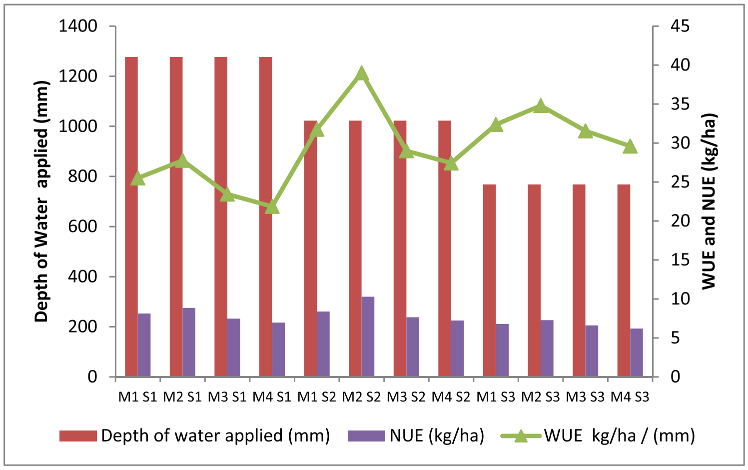
Interaction effect of mulching and various levels of irrigation also significantly influenced the fresh rhizome yield (Table 6). The crop raised with plastic mulch (50µ) along with 80% of pan evaporation through drip (M_2S_2) significantly increased yield (47,988 kg ha^{-1}) than other treatments. This treatment showed 39.79% higher yield compared with no mulch combined with 60% pan evaporation through drip fertigation (M_4S_3) (28,889 $kgha^{-1}$).

3.7. Water and nutrient use efficiency (WUE and NUE)

The highest Nitrogen Use Efficiency (NUE) and WUE was in plastic mulch (50µ) along with 80% of pan evaporation through drip 39.01 kg/ha mm^{-1} and 319.92 $kgha^{-1}$ (M_2S_2) as compared with other treatments. Results showed that application of plastic mulch (50µ) along with 80% of pan evaporation through drip system of irrigation resulted in significantly greater Water Use efficiency (WU)E with 24.88% less water use than 60% of pan evaporation + no mulch treatment (Fig. 4). This might be due to the higher soil moisture content in mulched plots than the other treatments (Data not shown). This could be attributed due to favorable microclimate near the root zone under mulching as stated earlier resulting in increased soil temperature and moisture retention conditions, which is due to less evaporation under mulching resulting in increased soil moisture. The lower WUE is 21.86 kg ha mm^{-1} in no mulch along with 100% pan evaporation (M_4S_1) and NUE lower in (192.59 $kgha^{-1}$) 60% pan evaporation with no mulch (M_4S_3). But in the case of non-mulched conditions even with the larger quantity of

Table 8
Influence of various mulching materials on the population of bacteria, fungi and actinomycetes in soil.

Treatments	Bacteria Population (cfu g^{-1}) ($\times 10^6$)			Fungi Population (cfu g^{-1}) ($\times 10^3$)			Actinomycetes Population (cfu g^{-1}) ($\times 10^4$)		
	At planting	120 DAP	At Harvest	At Planting	120 DAP	At Harvest	At planting	120 DAP	At Harvest
Main plot									
M_1	44.40	44.23	28.28	42.65	35.25	44.75	69.56	62.25	115.40
M_2	48.20	43.35	26.00	41.00	34.12	40.75	72.25	59.75	108.50
M_3	46.50	50.28	34.00	45.75	39.75	52.50	76.25	67.30	124.50
M_4	37.50	44.21	25.00	44.50	32.25	39.75	80.25	58.25	94.50
Sub plot									
S_1	48.50	53.10	32.75	44.70	39.10	52.50	78.90	70.10	119.75
S_2	50.10	56.75	36.75	47.80	42.50	56.75	84.10	73.58	126.80
S_3	46.40	50.20	30.50	42.75	36.20	46.80	73.90	67.25	115.75



M_1- 25 micron Plastic Mulching; S_1- 100 % of pan evaporation ; M_2- 50 micron Plastic Mulching,S_2- 80% of pan evaporation
M_3- Organic Mulching, S_3- 60% of pan evaporation, M_4- No Mulching

Fig. 4. Influence of drip irrigation and mulching on Depth of water applied (mm), WUE and NUE of turmeric.

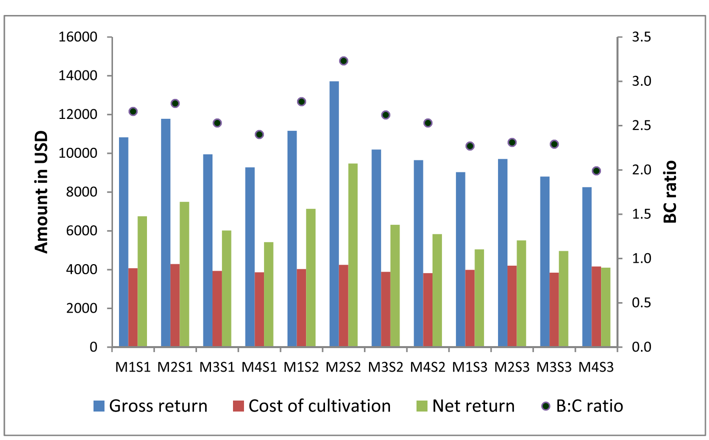
irrigation yield cannot be improved and resulting in lower WUE and NUE [62,64,68]. Palada et al. [69] and Ertek et al. [70] also reported similar results. In the presence of water, Nitrogen has a favorable interaction effect with other nutrients, according to Aulakh and Malhi [71].

3.8. Post-harvest nutrient uptake

Post-harvest nutrients uptake was highly influenced by the mulching along with various levels of drip irrigation system along with fertigation. Nitrogen (N), Phosphorus (P) and potassium (K) uptake showed a highly positive influence by different treatments during all the stages of observations (Table 7). Polyethylene mulching at 50, 25 μm and organic mulch resulted in significantly higher uptake of NPK at 240 DAS, respectively, when compared to the no mulch treatment. Mulch alone could increase soil uptake ranges from 3.67 to 9.57 per cent than without mulching (control). This is similar to some of the earlier studies which reported the positive effect of polyethylene mulching in tomato and okra [64,72–74]. Drip irrigation with 80% pan evaporation (PE) along with the fertigation was statistically significant with the maximum nutrient uptake of N (262 kg ha^{-1}), P (23 kg ha^{-1}) and K (218 kg ha^{-1}) at 240 DAS, respectively. The highest uptake of nutrients is due to effect of improved turmeric rhizome yield. The highest yield was due to the higher WUE (water use efficiency) when compared to the control in which hypoxia might have been caused due to flooding. But in the case of drip fertigation, plant root zone is well aerated [75] with sufficient soil moisture leading to nutrient availability and resulting in higher nutrient uptake [52].

3.9. Economic feasibility

Economic profitability analysis showed that treatment M_2S_2 showed a higher Benefit Cost value of 3.23 with a profit of Rs.6, 62,760 ha^{-1} and least net profit of Rs.2, 86,780 ha^{-1} with a B: C ratio of 1.99 was observed in treatment M_4S_3 (Fig. 5). Mulching treatments along with 80% pan evaporation (PE) based irrigation gave higher profitability than the other treatments such as control and no mulching along with 60% pan evaporation through drip irrigation. Proper and consistent nourishment of soil by up keeping the moisture content in the desired level (within field capacity) during entire crop period is the key strategy behind the drip irrigation technique. Profitability analysis confirmed that drip fertigation system is profitable when compared to the other treatments [64,76].



M_1- 25 micron Plastic Mulching; S_1- 100 % of pan evaporation ; M_2- 50 micron Plastic Mulching,S_2- 80% of pan evaporation
M_3- Organic Mulching, S_3- 60% of pan evaporation, M_4- No Mulching

Fig. 5. Influence of drip irrigation system and crop mulch on gross return (USD./ha), cost of cultivation (USD/ha), net return (USD/ha) and benefit cost ratio of turmeric.

3.10. Simulated water saving

Data on turmeric area for the State of Tamil Nadu showed that total cultivated area was 35,795 ha and it was dominant in the following districts, viz., Erode, Dharmapuri, Salem, Namakkal, Villupuram and Coimbatore. 80% of pan evaporation along with 50-μm Plastic Mulching resulted in higher yield and hence it has been assumed that if it is adopted for the entire state of Tamil Nadu, how much of water quantity can be saved was calculated. The results showed that it will result in saving of 9.15 mm^3 and each district-based area and quantity of water saved is shown in Fig. 6. Approximately, 20% of water can be saved if this technology is adopted and that water may assist in bringing more area under cultivation or it could have been used for other purposes [74, 77].

3.11. Influence of mulching on microbial population rhizosphere

The influence of mulching and drip fertigation on population of soil microbes demonstrated highly significant results, when compared to the population of microbes at planting, under the various treatments applied (Table 8). The higher population of microbes was noticed in the treatments of mulching and the lowest population was noted in the initial stage (37.5106 cfu per g) and later increased to (48.20,106 cfu per g) in M4 (no mulch) (Table 8). The favorable micro climatic conditions in the mulching treatments might have increased the soil bacterial population for all treatments [78]. After 120 days after planting, M3 treatment (Organic mulched plot) showed the higher population of bacteria and lowest was observed in M1 (25 μm black polythene mulch) treatment, which was similar with M4 treatment, statistically (no mulch). The largest bacterial count was reported in S2 (80 percent pan evaporation compared to 60 percent pan evaporation) drip fertigation treatments at 120 DAP (S3). Due to the predominance of high soil temperature, there was a significant decline in population of bacteria in soil from planting to maturity in almost all of the treatments. However, the population of fungi and actinomycetes in the soil increased from planting to maturity. Gopalkrishnan et al. [79] discovered that grass root exudates have an inhibitory effect on bacteria (2009).

In the organic mulched (M3) and plastic mulch (M2) treatments, population of fungus varied from 41.00 to 45.75 × 103 cfu per g, respectively in the initial stage (Table 8). At 120 DAP, it was discovered that the population of fungi in all the treatments had reduced from its original value and had steadily increased at maturity. M3 treatment (Organic mulch) had the greatest fungal population (39.75 × 103 cfu per g) in the mulched plot at 120 DAP, compared to no mulch (M4) treatments. M3 treatment (Organic mulch), on the other hand, had the largest fungal population (52.50 × 103 cfu per g) at harvest. The largest fungus count was reported in S2 (80 percent pan evaporation compared to 60 percent pan evaporation) drip fertigation regimes at 120 DAP (S3).

Population of actinomycetes microbes was in the range of 69.56–80.25 × 104 cfu per g in M1 (25 micro plastic mulch) and M4 (no mulched) plot at the initial stage of the experiment (Table 9). At sixty days after planting, it was noted that the population of actinomycetes in all treatments had reduced and later had steadily increased at maturity. In drip fertigation regimes, S2 treatment (80% pan evaporation) had the greatest population of actinomycetes (73.58 × 103 cfu per g) at 120 DAP, compared to S3 treatment (60 percent pan evaporation). However, the S2 treatment had the greatest population of actinomycetes (126.80 × 103 cfu per g) at harvest (80 percent pan evaporation). Thus, rhizosphere soil of turmeric showed higher actinomycetes population in the organic mulch treatment and it had a significant impact growth and yield of turmeric. In the control group, the minimum number of actinomycetes was found. Pal et al. [80] found that the population of actinomycetes in rhizosphere soil increased as the soybean crop matured, owing to increased carbon availability due to leaf-fall.

3.12. Degradation of plastics

Results on the degradation of plastic mulches under drip fertigation in soil for two species are shown in Table 9. The soil incubation results showed that plastic mulches were found to be degraded after 6 and 9 months, In the case of plastic cups, degradation was noticed only after 9 months, and not degraded in 2, 4 and 6 months of analysis. The biodegradation of polythene was found to be higher (3.77% and 4.21%) under *Rhizophora* and *Avicennia* zones respectively, after 9 months of analysis, and the biodegradation of plastics were only 0.25% and 0.17%.

Table 9
Biodegradation of plastic mulches buried for different duration under experimental plots.

Month of analysis	Biodegradation (% weight loss)	
	Rhizophora zone	Avicennia zone
2	0	0
4	0	0
6	1.98 ± 0.29	1.74 ± 0.12
9	3.77 ± 0.29	4.21 ± 0.31

Values between months of analysis are significant at 5%.

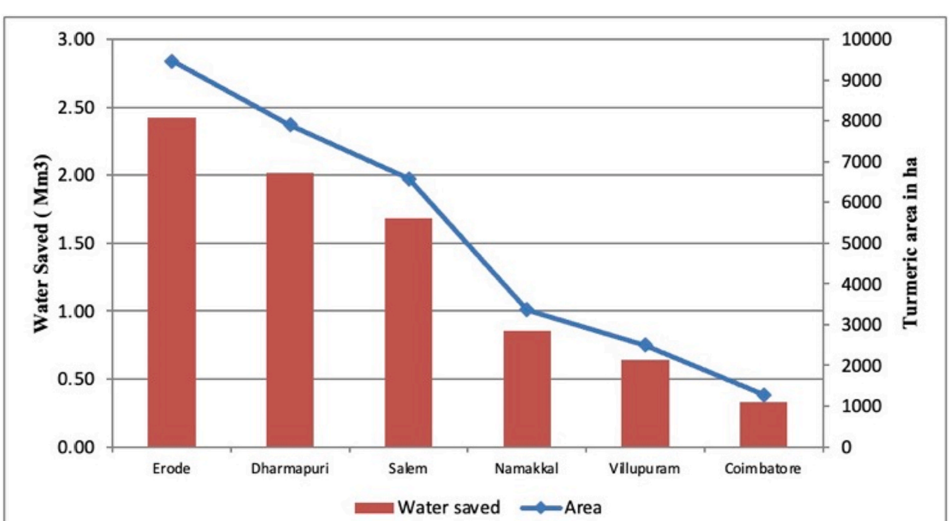


Fig. 6. District wise area and quantity of water saved if this technology is adopted.

While PE mulches are effective as a barrier in the surface, they have a very different fate when it comes to their final end. It is suggested that PE films need to be removed from the soil surface after the growth season is completed. Before they are totally biodegraded, this mulch pieces can alter the physical properties of the soil. Micro particles from these PE plastics, may reduce infiltration rate of the soil and that may influence the absorption capacity of water [81–89]. As a result, it's possible that in such conditions can limit soil microbial activity (e.g., water scarcity).

Plastic mulches contain a variety of organic substances in the form of additives, plasticizers, and inorganic constituents in the form of Cu, Ni, etc, the consequences of which are harmful and for some of them mostly unknown. A phytotoxicity analysis of many constituents of bioplastics revealed that some of them inhibited plant development based on its concentrations ([82]). Maize root and shoot development were harmed by acrylate polymers used to control soil humidity ([82–84]). Crop plants have been discovered to absorb organic chemicals produced by mulch polymers ([84–87]). Recently many researchers are attempted to study the effect of these additives and its derivatives on its impact in soils, microbial population and ultimately on plants Biodegradable mulches, such as Polyethylene films, have no measurable impact on soil nitrification potential, according to research ([87–90]); however, the impacts on other nutrients are unknown. Early research attempts to have plastic mulches that degrade in the field at the end of growing season revealed that micro and nano plastics are being produced upon degradation which may present in the soil for longer duration ([81]).

4. Conclusions

The research findings conclusively highlight the superiority of employing drip irrigation at 80% pan evaporation with fertigation alongside polyethylene mulching (50μ) in achieving the highest yield in turmeric. This combination not only demonstrates cost-effectiveness but also proves more profitable compared to scenarios involving no mulching with 60% pan evaporation. The experimental investigation validates that implementing drip irrigation with fertigation and polyethylene mulching significantly enhances turmeric yield, showcasing a remarkable 39.79% increase over the utilization of 60% pan evaporation without mulch. Moreover, the research sheds light on the impact on microbial populations and the degradation of mulches, providing insights into the broader ecological implications of these agricultural practices. Economically, employing polyethylene mulching (50μ) in conjunction with 80% pan evaporation through drip irrigation (M2S2) significantly enhances economic profitability (net profit) by 56.72% when compared to using 60% pan evaporation without mulching (M4S3). These findings confirms that the substantial economic benefits and agricultural advantages of adopting drip irrigation with fertigation, and polyethylene mulching in enhancing turmeric yields, optimizing resource usage, and promoting sustainable agricultural practices in such agro-climatic conditions. Hence it is recommended that policy makers, department of agriculture and extension officials should actively advocate for the adoption of these integrated technologies to attain increased yields, improved profitability, and environmental sustainability.

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CRediT authorship contribution statement

Jayakumar M: Methodology, Conceptualization. **S. Santhana Bosu:** Visualization, Validation. **Komali Kantamaneni:** Writing – review & editing. **Upaka Rathnayake:** Visualization, Validation. **Surendran U:** Writing – original draft, Software, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rineng.2024.102018.

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