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RESEARCH PAPER

Estimation of Broccoli Crop Water Requirement under Variable Microclimatic Conditions of Different Protected Structures and Open Field

M.A. Sojitra[1]*, P.M. Kyada[2] and R.M. Satasiya[3]

[1]Assistant Professor, Department of Soil and Water Conservation Engineering, Anand Agricultural University, Godhra, Gujarat, India
[2]Assistant Research Scientist, Farm Science Centre, Lokbharati, Sanosara, Gujarat, India
[3]Principal, Polytechnic in Agricultural Engineering, Junagadh Agricultural University, Targhadia, Gujarat, India

*Corresponding author: manojsojitra@aau.in (**ORCID ID:** 0000-0002-3479-8634)

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ABSTRACT

Protected cultivation structures create favorable microenvironments for crop growth, enabling higher yields and improved produce quality. This study evaluated microclimatic parameters *viz.* temperature, relative humidity, solar radiation and light intensity under a Naturally Ventilated Net-cum-Poly House (NVNPH), a shade-net house, and open-field conditions. Two years of daily meteorological data (2020–21 and 2021–22) were used to characterise the microclimate of each structure, and the FAO-56 Penman–Monteith method was applied to estimate reference crop evapotranspiration under each condition. The shade-net house and NVNPH reduced incident solar energy and moderated internal temperature relative to the open field. Total water requirement for drip-irrigated, soilless broccoli cultivation was reduced by 58.69% under the shade-net house and 51.49% under the NVNPH relative to open-field cultivation.

HIGHLIGHTS

- FAO-56 Penman–Monteith method used to estimate broccoli water requirement under protected structures and open field.
- Local grow-bag conditions required substantial correction of standard FAO-56 crop coefficients.
- Shade-net house and NVNPH saved 58.69% and 51.49% irrigation water over open field, respectively.

Keywords: Broccoli, Crop coefficient, Evapotranspiration, Protected cultivation, Water saving

Water is fast becoming one of the most limiting resources for future agricultural production. Global freshwater demand continues to rise with population growth, and agriculture already accounts for the largest share of consumptive water use worldwide (O'Connor and Mehta, 2016). This pressure is compounded by increasingly erratic rainfall and rising temperatures associated with climate change, both of which make open-field vegetable production less reliable and push growers toward technologies that combine higher yield with lower water use. Protected structures such as poly-houses, net-houses, shade-net houses and their hybrids have consistently been shown to reduce crop evapotranspiration relative to open-field conditions by moderating solar radiation, wind speed, air temperature and relative humidity around the canopy, while also offering protection against insect pests and disease (Santosh *et al.* 2017; Singh *et al.* 2016; Hashem *et al.* 2011).

Broccoli (*Brassica oleracea* L. var. italica) is a nutritionally important cole crop whose growth,

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floral initiation and head quality are strongly governed by incident radiation and temperature. Controlled-shading studies have shown that broccoli tolerates moderate reductions in intercepted photosynthetically active radiation (PAR) with little yield penalty, whereas heavier shading delays maturity, alters dry-matter partitioning among leaves, stem and spear, and can depress commercial yield (Francescangeli *et al.* 2007; Nooprom *et al.* 2013). Deficit-irrigation trials on field-grown broccoli have further shown that yield and quality attributes — head diameter, floret number and ascorbic acid content — are highly sensitive to the fraction of full crop water requirement supplied, with economically viable yield generally obtained only when at least 70% of full irrigation is met (Durak and Yıldırım, 2017). These findings indicate that structure type and irrigation regime jointly, rather than independently, determine the water economy and productivity of broccoli.

Accurate estimation of crop water requirement is central to designing efficient irrigation schedules, particularly for high-value protected crops under drip irrigation. The FAO-56 Penman–Monteith method remains the internationally recommended standard for estimating reference evapotranspiration (ET_0), integrating the principal meteorological drivers of evapotranspiration — net radiation, air temperature, relative humidity and wind speed — into a single physically based equation (Klar and Fontes, 2003; Singh *et al.* 2016). Crop evapotranspiration (ETc) is obtained by applying a crop coefficient (Kc) to ET_0, with Kc requiring local adjustment for planting density, canopy development, ground cover and irrigation method, as prescribed in FAO Irrigation and Drainage Paper 56. This framework has been widely applied to vegetable and ornamental crops in protected structures, consistently showing lower ET_0 and ETc under cover than in the open field due to reduced wind speed, moderated radiation and elevated humidity (Hashem *et al.* 2011; Zhang et al., 2010; Singh *et al.* 2016; Santosh *et al.* 2017). However, Kc values specific to broccoli grown in soilless media under drip irrigation, compared simultaneously across NVNPH, shade-net house and open-field conditions, remain scarce.

Soilless cultivation is increasingly combined with protected structures to further tighten water and nutrient management, since substrate-based systems restrict the wetted volume, avoid evaporative losses from a large exposed soil surface, and allow drip-applied water to closely track crop demand (Agung Putra and Yuliando, 2015). Kc curves derived for field-grown broccoli require correction before application to soilless, drip-irrigated systems, because evaporation from a small grow-bag surface differs from evaporation across an open field or soil-based crop row, particularly during early vegetative growth when ground cover is incomplete.

Given this background, the present study estimated reference evapotranspiration under NVNPH, shade-net house and open-field conditions using the FAO-56 Penman–Monteith method, and quantified the resulting crop water requirement and percentage water saving achieved under each protected structure relative to open-field cultivation over two consecutive growing seasons.

MATERIALS AND METHODS

Experimental site and duration

The experiment was conducted at the Green House Complex, Department of Renewable Energy Engineering, College of Agricultural Engineering and Technology, Junagadh (21.52°N, 70.47°E; altitude 107 m MSL). The site has a subtropical, semi-arid climate with cold, dry winters, hot, dry summers, and warm, moderately humid monsoons. Weekly mean daily maximum and minimum temperatures ranged from 29.5–39.4°C and 10–26.7°C, respectively; relative humidity ranged from 51–81%; mean wind speed was 10.1 km/h; bright sunshine hours ranged from 4.2–13.4 h; and pan evaporation ranged from 3.6–10.7 mm. The 35 years of average annual rainfall and evaporation were 950 mm and 2482 mm, respectively.

The study spanned two consecutive growing seasons (2020–21 and 2021–22) to capture year-to-year weather variability and allow cross-checking of derived crop coefficients between seasons. Broccoli was cultivated simultaneously under three treatments representing a gradient of microclimatic modification: (i) NVNPH, (ii) a shade-net house, and (iii) an open-field unprotected (Control). Locating all three treatments within the same experimental area ensured that differences in evapotranspiration and irrigation requirement could be attributed to the covering structure rather than to site-to-site variation in soil or regional climate.

Description of protected cultivation structures

The NVNPH combined a 200 µm UV-stabilised polyethylene roof with net-covered side openings, permitting passive ventilation while trapping a fraction of incoming solar radiation and moderating wind speed, following construction principles described for saw-tooth and net-cum-poly structures in earlier protected-cultivation trials (Satasiya *et al.* 2024; Santosh *et al.* 2017; Singh *et al.* 2016; Table 1, Fig. 1). The shade-net house consisted of a framed structure clad with 50% white shade net on the roof and sides, providing defined shading of incident radiation while allowing greater air exchange than the poly-covered structure, consistent with shade-net designs reported for broccoli, cucumber and other vegetable crops (Nooprom *et al.* 2013; Hashem *et al.* 2011; Table 2, Fig. 2). The open-field plot, adjacent to both structures, served as the unprotected reference treatment representing conventional cultivation, against which water savings were expressed.

Table 1: Specifications of the natural ventilated greenhouse structure

Sl. No.	Particular	Details
1	Floor area	12.0 m × 5.00 m
2	Eave height	4.00 m
3	Ridge height	5.30 m
4	Orientation	East–West
5	Cooling mechanism	Natural ventilation
6	Structure covering	Roof: 200 µm UVS plastic; Side: 50% white net

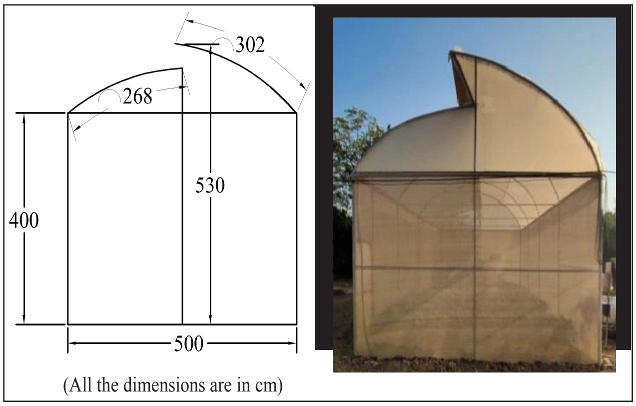

Fig. 1: Natural ventilated net-cum-poly house

Table 2: Specifications of the shade-net house structure

Sl. No.	Particular	Details
1	Floor area	12.0 m × 5.00 m
2	Eave height	4.00 m
3	Ridge height	5.30 m
4	Orientation	East–West
5	Cooling mechanism	Natural ventilation
6	Structure covering	Roof and sides: 50% white shade net

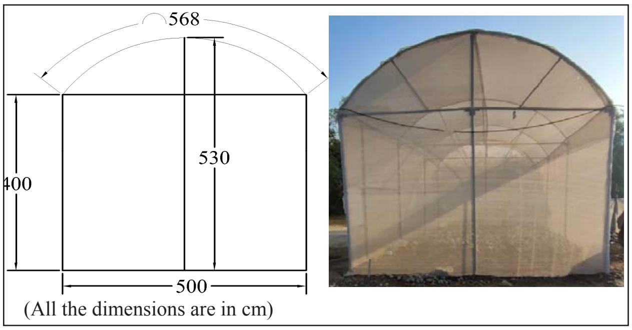

Fig. 2: Shade-net house

Micrometeorological monitoring

Daily meteorological data — maximum and minimum air temperature, maximum and minimum relative humidity, solar insolation and bright sunshine hours — were recorded within each structure and in the open field throughout both growing seasons. Wind speed was recorded in the open field only, as air movement inside the structures was minimal; Wang *et al.* (1999) similarly reported wind velocity below 0.1 m/s at the centre of a naturally ventilated greenhouse, consistent with the present observations. These parameters constitute the principal inputs of the FAO-56 Penman–Monteith equation and were used to characterise the distinct microclimates of each structure and to drive ET_0 calculations (Allen *et al.* 1998; Klar and Fontes, 2003).

Crop establishment and soilless cultivation system

Broccoli was raised in a soilless substrate system to standardise the rooting medium across treatments and minimise confounding effects of native soil variability on water uptake, following the rationale for soilless culture in water-use-efficiency studies (Agung Putra and Yuliando, 2015). Plants were grown in individual grow bags (20 × 20 × 25 cm, *L* × *W* × *H*) filled with an inert soilless medium, at 0.30 m × 0.30 m spacing, replicated identically across the NVNPH, shade-net house and open-field treatments. Irrigation in all treatments was delivered via drip system, enabling precise, scheduled water application to the root zone and accurate measurement of the irrigation volume applied at each growth stage.

Estimation of reference evapotranspiration (ET_0)

Reference evapotranspiration was estimated separately for the NVNPH, shade-net house and open-field conditions using the FAO-56 Penman–Monteith equation 1:

$$ET^0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right)u_2(e_S - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET^0 is reference evapotranspiration (mm day^{-1}), R_n is net radiation, G is soil heat flux density, T is mean daily air temperature, u_2 is wind speed at 2 m height, ($e_s - e_a$) is saturation vapour pressure deficit, Δ is the slope of the saturation vapour pressure curve, and γ is the psychrometric constant (Allen *et al.* 1998; Klar and Fontes, 2003; Singh *et al.* 2016). Structure-specific daily meteorological records were used so that radiation, humidity and wind terms reflected the actual microclimate experienced by the crop rather than a single ambient value applied uniformly across treatments, consistent with comparative ET_0 studies of protected and open-field vegetable production (Hashem *et al.* 2011; Santosh *et al.* 2017).

Crop coefficient (K_c) determination and adjustment

Standard FAO-56 crop coefficients for broccoli at the initial, mid and end stages were taken from tabulated values recommended for drip-irrigated conditions (FAO-56) as the starting reference. Since these values assume a fully developed crop occupying the entire field area, they were corrected for local conditions following the FAO-56 adjustment procedure (Allen *et al.* 1998), which accounts for climatic conditions during the mid- and late-season stages and, in this study, additionally for the restricted wetted/exposed surface area of individual grow bags.

At the initial stage, evaporative loss occurs predominantly from the exposed grow-bag surface rather than a continuous soil surface; K_c initial was therefore scaled to the fraction of ground area occupied by the grow-bag footprint relative to plant spacing, reflecting the transition from evaporation-dominated to transpiration-dominated water loss as canopy cover develops. As canopy cover approached completeness at mid-season, transpiration became dominant, and K_c mid was retained close to the standard FAO-56 value, consistent with broccoli's close-growing canopy (cover ratio approaching 1). Kc end was adjusted downward from the peak mid-season value to reflect declining canopy activity as the crop approached commercial maturity. Growth stages (initial, mid, end/late) were delineated in days after sowing (DAS), consistent with staging conventions used in comparable broccoli and vegetable evapotranspiration studies (Klar and Fontes, 2003; Durak and Yıldırım, 2017).

Crop evapotranspiration and irrigation scheduling

Daily crop evapotranspiration (ET_c) for each treatment was calculated as the product of the structure-specific ET_0 and the locally adjusted K_c for the corresponding growth stage:

$$ET_c = K_c \times ET_0$$

Irrigation water was applied via the drip system according to the estimated ET_c for each growth stage, with the volume delivered recorded for each treatment across both growing seasons, mirroring the irrigation-scheduling approach used in other FAO-56-based protected-cultivation studies (Santosh *et al.* 2017; Singh *et al.* 2016).

Data analysis and water-saving assessment

Seasonal irrigation applied under the NVNPH and shade-net house treatments was compared with that applied under open-field cultivation to compute percentage water saving:

$$\textit{Water saving}\ (\%) = \frac{(\text{Irrigation applied in open field} - \text{Irrigation applied under structure})}{\text{Irrigation applied in open field}} \times 100$$

Mean irrigation depths (mm) were compared between the 2020–21 and 2021–22 seasons for each treatment to assess the consistency of the microclimatic and water-saving effects across years.

RESULTS AND DISCUSSION

Crop water requirement

Reference evapotranspiration (ET_0) is the principal parameter required to estimate crop water requirement. It depends on atmospheric conditions at a given location and time of year, independent of crop and soil characteristics, and is governed primarily by solar radiation, air temperature, humidity and wind speed. The FAO-56 Penman–Monteith method is the most widely recommended approach for estimating ET_0, as it closely approximates measured grass-reference evapotranspiration using location-specific physiological and aerodynamic parameters. Solar radiation, maximum and minimum air temperature, maximum and minimum relative humidity, bright sunshine hours and wind speed were used to calculate ET_0 in this study.

Crop coefficient values under soilless conditions

The standard FAO-56 crop coefficients for drip-irrigated broccoli — K_c initial, K_c mid and K_c end — are 0.70, 1.05 and 0.95, respectively (FAO-56, Table 3); FAO-56 recommends adjusting these values for local conditions. Moisture loss (evaporation plus transpiration) depends on temperature, relative humidity, wind speed, sunshine, solar radiation, crop stage and ground cover. In this study, broccoli was grown in grow bags (20 × 20 × 25 cm) filled with soilless medium, and evaporation initially occurred only from the exposed bag surface. Evaporation dominates at early growth stages when the crop is small, while transpiration becomes dominant once the crop achieves complete ground cover.

Crop water requirement was maximal when canopy spread was complete, at which point transpiration remained the dominant process; broccoli's canopy cover ratio at this stage approaches 1. Because K_c initial was scaled to the grow-bag footprint relative to the 0.30 m × 0.30 m plant spacing, the local K_c initial was reduced to 44–66% of the standard FAO-56 value. As only partial air movement occurred inside both protected structures, consistent with Wang *et al.* (1999), K_c mid and K_c end were not further adjusted from the standard FAO-56 values. The adjusted K_c initial, K_c mid and K_c end were therefore 0.33, 1.05 and 0.95, respectively (Table 3, Fig. 3).

Table 3: Standard and locally adjusted Kc values for broccoli

Growth stage	DAS	Standard FAO-56 K_c	Adjusted K_c
Initial	0–28	0.75–1.05	0.33
Mid	28–56	1.05	1.05
End	57–77	1.05–0.95	0.95

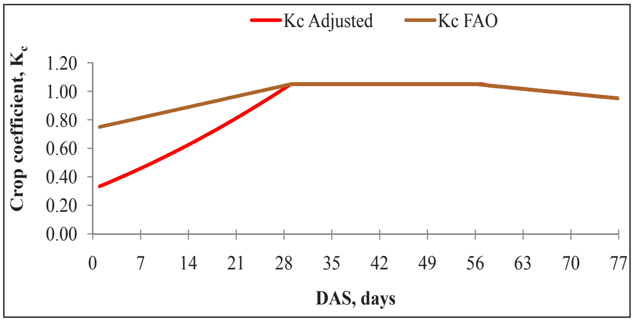

Fig. 3: Locally adjusted crop coefficient (K_c) values for broccoli

Crop evapotranspiration (ET_c) and irrigation requirement

Reference evapotranspiration was calculated using the FAO-56 Penman–Monteith equation, and crop evapotranspiration (ET_c) was obtained as the product of ET_0 and the adjusted K_c. Irrigation was applied according to crop growth stage in both growing seasons (Table 4). Mean seasonal irrigation requirement was highest under open-field cultivation (270 mm), followed by the shade-net house (139 mm) and NVNPH (119 mm). Water saving relative to the open field was 51.49% under NVNPH and 58.69% under the shade-net house.

These results are consistent with Santosh *et al.* (2017), who reported water savings of 35.6%, 35.2% and 25.5% for drip-irrigated vegetable crops under shadow-hall, poly-house and shade-net house structures, respectively, relative to open-field cultivation. The higher savings observed in the present study likely reflect the additional water economy afforded by the soilless, grow-bag cultivation system, which restricts the wetted/

exposed surface area beyond what structural shading and ventilation alone achieve.

Table 4: Irrigation water applied to broccoli during 2020–21 and 2021–22.

Structure	2020–21 (mm)	2021–22 (mm)	Mean (mm)	Water saving (%)
NVNPH	119	118	119	51.49
Shade-net house	139	138	139	58.69
Open field	281	259	270	–

CONCLUSION

Reference evapotranspiration, estimated via the FAO-56 Penman–Monteith method, depends solely on local atmospheric conditions, independent of crop and soil factors. Standard FAO-56 crop coefficients for broccoli required significant local correction under soilless, grow-bag cultivation, particularly Kc initial, which fell to 0.33 (from 0.70) due to the restricted evaporative surface of the grow bag, while K_c mid (1.05) and K_c end (0.95) remained close to standard values as canopy cover approached completeness. Applying these adjusted coefficients showed markedly lower irrigation requirement under protected structures than in the open field (270 mm), with water savings of 51.49% (NVNPH) and 58.69% (shade-net house). Overall, protected structures — especially the shade-net house — substantially reduce broccoli's water footprint, supporting the use of locally adjusted crop coefficients over standard FAO-56 values for irrigation scheduling of soilless, drip-irrigated broccoli.

GENERATIVE AI DECLARATION

The author(s) confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript, and no images were manipulated using AI. The authors developed and verified all scientific content, data analysis, interpretation of results, and conclusions. The authors take full responsibility for the accuracy, integrity, and originality of the work presented, and no AI tool was listed as an author.

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