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REVIEW

Single and basal crop coefficients for estimation of water requirements of subtropical and tropical orchards and plantations with consideration of fraction of ground cover, height, and training system

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Abstract

This paper provides an overview of the research carried out over the last 25 years on the FAO56 single and basal crop coefficients of subtropical and tropical orchards and plantations of cactus pear, dragon fruit, fig, jujube, passion fruit, pomegranate, cape gooseberry, cherimoya, guava, longan, lychee, mango, papaya, acerola, carambola, cashew, cacao, coffee, jaboticaba, jatropha, macadamia, açai palm, coconut, date palm, guayule, oil palm, peach palm, ramie and rubber tree. The main objective of this review is to update standard single crop coefficients (K_c) and basal crop coefficients (K_{cb}) and complete the K_c and K_{cb} values tabulated in FAO56. K_c is the ratio between the non-stressed crop evapotranspiration (ET_c) and the grass reference evapotranspiration (ET_o), and K_{cb} is the ratio between the crop transpiration (T_c) and the ET_o. When selecting and analysing the literature, only studies that used the FAO Penman–Monteith equation, or another equation well related to the former to compute ET_o were considered, while ET_c or T_c were obtained from accurate field measurements on crops under pristine (non-stress cropping conditions) or eustress ("good stress") conditions. Articles meeting these conditions were selected to provide data for updating K_c and K_{cb} under standard conditions. The related description of orchards and plantations refers to crop cultivar and rootstock, irrigation systems and scheduling, planting spacing, fraction of ground cover (f_c) by the crops, crop height (h), crop age and training systems, as K_c and K_{cb} values depend on these characteristics. To define the standard K_c and K_{cb} values of the selected crops, the values collected in the literature were compared with previously tabulated standard K_c and K_{cb} values. The updated tabulated values are transferable to other locations and climates and can be used to calculate and model crop water requirements, primarily for irrigation planning and scheduling, and thereby supporting of improved water use and savings, which is the overall aim of the current review.

Abbreviations

A&P	Allen and Pereira (2009) approach
AGC	Active ground cover
Avg.	Average
BREB	Bowen ratio energy balance
BS	Bare soil
Capac	Capacitance sensors
DI	Deficit Irrigation
DL	Drainage lysimeters
DPS	Density of plants and spacing
EC	Eddy covariance
FAO-PM-ET_o	Grass reference ET_o computed with full data
FDR	Frequency Domain Reflectometry
FI	Full irrigation
grav.	Gravimetric method
LAI	Leaf area index
Lys.	Lysimeter
Med	Mediterranean
Mic-spr	Micro-sprinkler or micro-sprayer
ML	Mini or micro lysimeters

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n/r	Not reported
NDVI	Normalized Difference Vegetation Index
OPEC	Open-Path Eddy-Covariance
Pl mulch	Plastic mulch
PM-eq.	Penman–Monteith combination equation
RDI	Regulated Deficit Irrigation
RS	Remote sensing
SDI	Sustained Deficit Irrigation
SEB	Surface energy balance
SF	Sap flow
Spr.	Sprinkler
SR	Surface renewal
SWB	Soil water balance
TDR	Time domain reflectometer
Ten.	Tensiometers
VI	Vegetation index
WL	Weighing lysimeter

List of symbols

ET_c	Crop evapotranspiration under standard conditions [$mm\ d^{-1}$ or $mm\ h^{-1}$]
$ET_{c\ act}$	Actual crop evapotranspiration, i.e., under non-standard conditions [$mm\ d^{-1}$ or $mm\ h^{-1}$]
ET_o	(Grass) reference crop evapotranspiration [$mm\ d^{-1}$ or $mm\ h^{-1}$]
f_c	Fraction of soil surface covered by vegetation [–]
f_{IPAR}	Fraction of the intercepted PAR [–]
F_r	Adjustment factor relative to stomatal control [–]
G	Soil heat flux density [$MJ\ m^{-2}\ d^{-1}$]
h	Crop height [m]
H	Sensible heat flux [$MJ\ m^{-2}\ d^{-1}$]
K_c	(Standard) crop coefficient [–]
$K_{c\ act}$	Actual crop coefficient (non-standard conditions) [–]
$K_{c\ avg}$	(Standard) average crop coefficient [–]
$K_{c\ ini}$	Crop coefficient during the initial growth stage [–]
$K_{c\ mid}$	Crop coefficient during the mid-season stage [–]
$K_{c\ end}$	Crop coefficient at end of the late season stage [–]
K_{cb}	Standard basal crop coefficient [–]
$K_{cb\ act}$	Actual basal crop coefficient (non-standard conditions) [–]
$K_{cb\ ini}$	Basal crop coefficient during the initial stage [–]
$K_{cb\ mid}$	Basal crop coefficient during the mid-season stage [–]
$K_{cb\ end}$	Basal crop coefficient at end of the late season stage [–]
K_s	Water stress coefficient [–]
M_L	Multiplier relative to the canopy transparency [–]
r_a	Aerodynamic resistance [$s\ m^{-1}$]
r_s	Bulk crop-soil surface resistance [$s\ m^{-1}$]
R_n	Net radiation at the crop surface [$MJ\ m^{-2}\ d^{-1}$]
T_c	Crop transpiration [$mm\ d^{-1}$ or $mm\ h^{-1}$]
λET	Latent heat flux [$MJ\ m^{-2}\ d^{-1}$]

Introduction

Knowledge of the water requirements of orchards and plantations is essential for planning and management of crop water use, assessing the balance between water resources availability and demand at farm and basin level, and developing basin hydrological studies. Accuracy in evapotranspiration estimates is essential, mainly when water scarcity prevails, so breaking the trend for water over-use and, contrarily, if sustainable irrigation is a must (Pereira et al. 2009). As reviewed by Pereira (2017), considering the continuously increase on demand for food, droughts and climate change, high water use performance and productivity and water conservation and saving require improved knowledge of crop evapotranspiration and water use. Therefore, literature on management of fruit crops is extensive relative to water management and deficit irrigation (DI) but requiring further information on crop water requirements.

Crop evapotranspiration (ET_c) is commonly computed or modelled using the FAO calculation procedure (Allen et al. 1998), which uses the simple K_c-ET_o approach to compute ET_c, i.e. the product of a crop coefficient (K_c) by the grass reference evapotranspiration (ET_o). The latter is computed with the FAO-PM ET_o equation (Allen et al. 1998) and is defined as the evapotranspiration rate of a (hypothetical) grass reference crop with fixed height of 0.12 m, a surface resistance of 70 $s\ m^{-1}$ and an albedo of 0.23, closely resembling an extensive surface of green grass of uniform height, actively growing, adequately watered, and well covering the ground (Allen et al. 1998). The daily ET_o equation corresponds to the Penman–Monteith combination equation parameterized for that grass crop with fixed and well defined aerodynamic and surface resistance terms (Allen et al. 1998; Pereira et al. 1999). The hourly ET_o is defined by Allen et al. (2006) and the daily ET_o ($mm\ d^{-1}$) is defined with the following equation:

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T+273} u_2 \left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \quad (1)$$

where Δ is the slope of the saturation vapor pressure–temperature curve at mean air temperature (kPa °C^{-1}), ($R_n - G$) is the available energy at the vegetated surface (MJ m^{-2} d^{-1}), γ is the psychrometric constant (kPa °C^{-1}), T is mean daily air temperature (°C), u_2 is mean daily wind speed (m s^{-1}) at 2 m height and ($e_s - e_a$) is the vapor pressure deficit (VPD) of the atmosphere (kPa). All fluxes are assumed to be vertical and horizontal local advective fluxes are not considered.

ET_o incorporates most of the weather and related energy effects, thus representing the evaporative demand of the atmosphere. Standard, transferable crop coefficients must be obtained from the ratio between accurate potential ET_c field measurements under non-stress or eustress conditions, and ET_o computed with the FAO-PM ET_o (Allen et al. 1998). Eustress (also called "good stress") refers to crops grown under mild and controlled water stress that may favour yield quality. Hence, K_c variations should mainly be attributed to the specific crop characteristics comparatively to those of the grass reference and only for a limited extent to the climate. These conditions enable the transfer of standard K_c values between locations and climates, when local and/or regional advection is excluded, with K_c representing an integration of the effects of the main characteristics that distinguish, in terms of the energy balance, the grass reference crop from the crop under study (Allen et al. 1998; Pereira et al. 1999).

K_c values should not surpass 1.2. However, under advective conditions much larger transpiration and larger soil evaporation values may be observed (Allen et al. 2011; Evett et al. 2012b; Pereira et al. 2021a; Rallo et al. 2021). Otherwise, if advection is not considered, the energy balance reported to the crop shows that there is not enough energy for evaporation and such overestimated K_c values are due to flaws in measurements or in computations. For application in small or isolated areas of vegetation, K_c can exceed the limits for grass reference (1.2–1.4), while for large areas, or small areas surrounded by vegetation with similar roughness and soil water status, K_c values must stick to values equal or smaller than those limits (Allen et al. 2011), as also discussed in the companion paper by Pereira et al. (2023).

FAO56 (Allen et al. 1998) introduced the partition of ET_c into soil evaporation (E_s) and crop transpiration (T_c), i.e., $ET_c = T_c + E_s$. Thus, we also have $K_c = K_{cb} + K_e$, sum of the basal crop coefficient (K_{cb}) with the soil evaporation coefficient resulting $T_c = K_{cb}\ ET_o$ and $E_s = K_e\ ET_o$. That partition is well described by Allen et al. (1998, 2005). Important to note from now that the K_c-ET_o approach is simple but requires the application of accurate measurements and computations, particularly when deriving K_c values for a crop using field observations (Allen et al. 2011; Pereira et al. 2021a, b).

The concept of standard crop coefficient (K_c) implies its determination for a non-stressed crop or a eustressed crop, when a crop is submitted to a well-controlled deficit that reduces water applied but keeping yield at an upper level (Paço et al. 2019; Rallo et al. 2021; Pereira et al. 2023). Abundant research aimed at finding strategies for controlled water deficit at given periods, or in selected modes during the crop cycle, aiming that yields are not or are less affected (Allen et al. 2011; Rallo et al. 2021). Findings have shown that the full satisfaction of crop water demand is not the best approach but an eustress that keeps yields high and quality is improved (e.g. López-Urrea et al. 2012).

Accurate standard, transferable and updated K_c values obtained from literature review require that related ET_c data collection, models and model calibrations, as well as experimental set-ups, are exempt of biases caused by experimental flaws (Allen et al. 2011). Following the methodology adopted in a companion paper (Pereira et al. 2023), the selected references were checked to ensure that sufficient descriptions of ET_c measurement practices, crop management and related production environment were provided. Articles were also checked to detect possible computational flaws and shortcomings in data handling or in model calibration and validation. The possible influence of advection was also considered as K_c/K_{cb} values result biased and can only be used locally, thus not transferable (Allen et al. 2011; Pereira et al. 2023; Rallo et al. 2021).

The K_c-ET_o method, is the most common in practice but the selected literature reports numerous applications of the K_c-ET_o method using a variety of field methods as analysed in the companion paper by Pereira et al. (2023) and bibliography quoted there. Allen et al. (2011) and Evett et al. (2012a) performed sound reviews aimed at attaining good accuracy of ET data. In addition, Pereira et al. (2023) analysed other ET_c field methods different of the ones commonly used for FAO K_c-ET_o, also referred for tabulations of K_c/K_{cb} for vegetable and field crops (Pereira et al. , 2021a; b). In addition to the K_c/K_{cb} review studies, the new K_c/K_{cb} studies referred also used the determination of actual K_{cb} and K_c from actual field measurements of f_c and h adopting the Allen and Pereira (2009) approach (A&P approach). A test of the A&P approach was performed for a variety of annual and perennial crops, so confirming the adequateness of this approach to estimate K_{cb}/K_c for diverse orchards and plantations (Pereira et al. 2020b, 2021c). Moreover, using actual observations and the A&P approach is useful for controlling the quality of ET measurements and for extending observed K_{cb}/K_c to a range of characteristics of crops, including to those not previously studied as described in Pereira et al. (2023).

The A&P approach is based on defining K_{cb} values along the season as a function of a density coefficient (K_d) and a K_{cb} at maximum plant growth near full ground cover ($K_{cb\ full}$). On the one hand, the K_d describes the increase in K_{cb} with increasing vegetation density and amount as a function of the fraction of ground cover (f_c), mean plant height

(h) and a multiplier for $f_{c\ eff}$ relative to canopy density and shading (M_L) as described by Allen and Pereira (2009) and Pereira et al. (2020b). M_L sets an upper limit on the relative magnitude of transpiration per unit of ground area as represented by $f_{c\ eff}$ and reflects the density and thickness of the canopy. On the other hand, the $K_{cb\ full}$ is calculated as a function of mean plant height and adjusted for both stomatal control of transpiration (F_r) and climate. The F_r parameter applies a downward adjustment ($F_r \leq 1.0$) to $K_{cb\ full}$ and consequently to K_{cb}, if the vegetation has stronger stomatal control of transpiration than is typical for agricultural crops. Since the parameters of the A&P approach were previously estimated, the approach was used to assure the coherence of input data as by Pereira et al. (2023).

The objective of this review paper, in line with the companion papers by Pereira et al. (2023) and López-Urrea et al. (2024) but focusing in particular on orchard perennial crops from tropical and subtropical regions, consists of (1) reviewing updated single and basal crop coefficient values (K_c and K_{cb}) obtained under non-stress and eustress conditions, (2) tabulating the main characteristics and K_c influencing factors relative to those crops, and (3) establishing a new set of tabulated standard and transferable K_c and K_{cb} coefficients ready for use in a revised version of the FAO56 guidelines, or directly from the current paper. It is underlined that focusing on crops growing under pristine or non-stress conditions, refers to crops grown without restrictions on growth and evapotranspiration caused by soil water and salinity stress, reduced crop density, pests and diseases, weed infestation, or low fertility and nutrients (Pereira et al. 2023). In addition, the study and tabulation of standard K_c and K_{cb} is to provide for updated information and data to support farmers, managers and researchers on estimating crop water requirements and to provide for methodologies that may lead to improve yields, control sustainability impacts of irrigation, favour water saving and cope and mitigate climate change.

Selection and analysis of the used scientific literature

For transferability purposes, FAO56 adopted the concept of standard K_c or K_{cb} and ET_c (Allen et al. 1998), which refer to well-watered and pristine or eustress cropping conditions, that are often different from actual field conditions, frequently under-optimal due to insufficient (or non-uniform) irrigation, crop density, salinity, agronomic practices and soil management. The tabulated and, therefore, transferable values of K_c and K_{cb} refer to standard cropping conditions, which in case of orchards and plantations refers to adopting crop-specific eustress practices, i.e., limited stress practices that result in no or minimal reduction in maximum yield. These concepts and related terminology are progressively being accepted by the user communities (Pereira et al. 2015). However, the standard K_c and K_{cb} values for tree and vine crops vary with the fraction of ground cover and height (Allen and Pereira 2009; Jensen and Allen 2016; Pereira et al. 2020b) due to crop age and crop management, particularly crop training and crop density. The present review has shown that satisfactorily accurate K_c and K_{cb} values reported for the same crop show dissimilarity among locations, which may be due to differences in cultivar and rootstock, plant density, orchard management and pruning, training, fruit load and thinning, as well as soil properties, irrigation method and strategy, and soil-crop management practices (Minacapilli et al. 2009; Marsal et al. 2014; Rallo et al. 2021). This is also evident from the companion papers focused on Mediterranean and temperate crops (Pereira et al. 2023; López-Urrea et al. 2024). For these reasons, it has been successful to estimate actual crop coefficients from f_c and h as quoted before. K_c variability due to weather is less important than causes referred above. However, a correction of K_c for climate is proposed in FAO56, but could not be used because most papers did not provide weather data on the experiment.

Literature reporting field derived crop coefficients has shown diverse objectives and used quite different methodologies with variable accuracy. The bibliography reviewed and rejected was about the double of that selected because K_c values were just for local (site-specific) use, papers reported much insufficient information about the crop itself, methods and instrumentation used, cropping practices and training, which caused serious limitations to transferability. For further information about the transferability requirements the reader is referred to Pereira et al. (2021a, 2023). Limitations in the reviewed studies were similar to those reported by Pereira et al. (2023), and included:

(1) Adopting other than the standard FAO-PM-ET_o equation without possibilities to be adequately converted to that one.
(2) Using a K_c curve different from the standard segmented FAO K_c curve, such as a function of LAI, not allowing a clear definition of the K_c (and K_{cb}) values for the initial, mid-season and end-season stages, respectively $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$. However, approximate estimations of $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ could be made from the reported graphical or from tabulated information.
(3) Using non-standard cultivation conditions, e.g., using mulch for controlling E_s, or active ground cover for fighting erosion result in management-specific K_c values without comparing with a reference condition.
(4) Adopting deficit irrigation practices and not providing a reference for eustress conditions, then making that the reported $K_{c\ act}$ have only local interest.

(5) Reporting insufficient data and information on the experiment, then not making it possible to assume that methods and practices were adequate.
(6) Using K_c values transferred from other studies without performing an appropriate testing.

The requirements for field data quality acquisition by common methods are extensively described in Allen et al. (2011) and reviewed by Rallo et al. (2021). For instance, the commonly used techniques that recur to soil water balance methods to calculate ET_c were often referred (Evett et al. 2012b; Pereira et al. 2020a). Their main sources of error arise from the non-quantification of deep percolation and/or capillary rise, or from a poor design of the sampling procedures that may not represent adequately the trees stand, or due to lack of accuracy of computation when the calibration of parameters is inadequate or the selected algorithms are not appropriate (Pereira et al. 2020a). Remote sensing is also commonly used to estimate actual ET_c, using both vegetation indices (VI) and surface energy balance (SEB) models (Pôças et al. 2014, 2020; Karimi and Bastiaanssen 2015). Because orchards are discontinuous canopies that differentiate among them, namely due to crop species, planting densities, training, and soil management, remote sensing may lead to inaccuracies when results do not base upon appropriate validation using ground data.

The review focused on articles published after the FAO56 guidelines (Allen et al. 1998), until September 2023. A systematic review was conducted, initially focusing on the articles that cited FAO56 and referred to crop coefficients, using the scientific names of the target crops. Several search engines were used (e.g., Scholar google, Elsevier, Springer, Wiley, Csiro publishing, Scielo, Scopus) as well as different combination of keywords (crop coefficients, orchards, plants names and scientific names). Various languages were used for the search (English, Portuguese, Spanish, French, and Italian). Insufficiencies and inaccuracies referred before limit the transferability of reported K_c values, which obliged to operate a careful, non-automatic literature selection. Aspects referred above as causing limitations in the accuracy of reported data were carefully considered, i.e., determined rejection of available literature. Reported studies were selected when:

- Adopted the FAO-PM-ET_o equation or the ASCE-PM-ET_o equation, or other ET_o equation when its ratio to the FAO-PM-ET_o could be approximated.
- Presented data of two or more experimental seasons, or studies having various treatments, so that it was possible to understand if results were or not occasional. However, for crops yet not having a known K_c, a single set of data assumed with quality was accepted.
- Descriptions of experiments sufficient to accept their accuracy and that crops were not stressed.
- Adopted the FAO K_c curve, or a K_c-time curve that allowed to identify K_c or K_{cb} for, at least, the mid-season, preferably, also for the initial and end-season.
- Papers describing field studies using Bowen ratio energy balance (BREB) or eddy covariance (EC) systems that reported upon the upwind fetch conditions and the energy balance closure.
- Papers reporting on soil water balance (SWB) methods describing all the terms of the balance, the soil profile, the sensors used and location, the frequency of observations, and the model calibration and validation.
- Reporting on adequate setting and management of lysimeters, namely on avoiding ''oasis'' and ''cloth-line'' effects and correcting the evaporative surface when the plant canopy exceeded the lysimeter surface ("bloom effect").
- Studies using remote sensing describe adequate ground observations used for SEB or VI calibration/validation.
- The reported K_c values are acceptable (K_c up to 1.30 and $K_{cb} < K_c$), unless convincing explanations were given.

The assumed criteria made it possible to select a good number of studies, developed in a variety of countries and regions and covering numerous species. The standard values of K_c and K_{cb} tabulated were established considering the ranges of K_c and K_{cb} values collected in the selected literature and the values tabulated since 1998 in FAO56 (Allen et al. 1998), Allen and Pereira (2009), Jensen and Allen (2016), and Rallo et al. (2021). That work developed in the following steps:

1st: Grouping the various studies relative to every crop considering: (i) the density of plants and spacing (DPS); (ii) the fraction of ground cover (f_c); and (iii) the crop height (h).

2nd: For all the groups of papers, the ranges of $K_{c\ ini}$/$K_{cb\ ini}$, $K_{c\ mid}$/$K_{cb\ mid}$ and $K_{c\ end}$/$K_{cb\ end}$ were defined and included as columns of K_c and K_{cb} observed values in draft tables relative to every crop. For basing decisions, the ranges of previously tabulated K_c and K_{cb} values were also included as columns in that draft table.

3rd: Draft definition of the standard values for K_c/$K_{cb\ ini}$, K_c/$K_{cb\ mid}$ and K_c/$K_{cb\ end}$ for all crops through assessing the various ranges inscribed in each line of the draft tables relative to sets of DPS, f_c, and h.

4th: Defining the standard values for $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$ for all crops through the computation of the A&P approach (Allen and Pereira 2009; Pereira et al. 2020b) for every set of f_c and h using the parameters M_L and F_r available from Pereira et al. (2021c), or adjusting the parameters M_L and F_r for not previously validated values comparatively to crops with similar characteristics.

5th: Defining the standard K_c values by summing estimated values of K_e for each stage with the defined standard $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$. The estimated values of K_e were obtained from observing the differences (K_c-K_{cb}) in the selected papers and in the previously published Tables with consideration of changes in K_c due to rain, and assuming a reduced soil evaporation due to using drip or micro-sprinkling under the canopies, and/or for a large plant density, and for using mulches. Young plantations are assigned with larger K_e values. K_e were assumed smaller for the mid-season, particularly for deciduous crops, and for the evergreen crops.

6th: Consolidating the draft standard K_c and K_{cb} through comparing all values (i) for various plant densities and ground cover fractions of the same crop; (ii) for the various crops of the same group; and (iii) between K_c and K_{cb}.

The tables presenting the updated standard $K_{cb\ ini}$, $K_{cb\ mid}$ and $K_{cb\ end}$, and standard $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ show their values in the last two columns, while the first ones are those indicating plant density and training or trellis systems, f_c and h, as well as the values assumed for M_L and F_r relative to the initial, mid- and end-season stages, that may be useful for further uses of the A&P approach. Ranges of observed and previously tabulated $K_{c\ ini}/K_{cb\ ini}$, $K_{c\ mid}/K_{cb\ mid}$ and $K_{c\ end}$ $/K_{cb\ end}$ are also included for information to users.

The tabulated information on the characteristics of the orchards and plantations refer to cultivar and rootstock if applicable, the experiment location and climate, the method for determining the actual ET_c ($ET_{c\ act}$) and the reference ET_o, the irrigation system and strategy used, the plant spacing and density, the training or trellis system, the age and height of trees and the fraction of ground covered by the crop (f_c) or the fraction of intercepted photosynthetic active radiation (f_{IPAR}). Other factors affecting crop water requirements, such as pruning, fruit thining and fruit load, were not considered due to lack of information on all selected studies.

Another table presents the actual K_c and K_{cb} values derived from field determinations of crop ET or T, and the relevant data useful in analysing these K_c and K_{cb} values, namely to compare K_c/K_{cb} data among crops of the same or similar species. These actual K_c and K_{cb} values were used in conjunction with the previously tabulated standard values to derive the new standard values.

The current review article focuses on subtropical and tropical tree, shrubs, and vine crops as well as palm, fiber and rubber plantations. The grouping of crops was based firstly on the climate type, on deciduous or evergreen crops. The growth habit (vine, trees, shrubs) was also considered. The tabulated data are grouped as: (1) cactus pear, dragon fruit, fig, jujube, passion fruit, and pomegranate; (2) cape gooseberry, cherimoya, guava, lychee, mango, and papaya; (3) acerola, carambola, cashew, cacao, coffee, jaboticaba, jatropha, and macadamia; (4) açai palm, coconut, date palm, guayule, oil palm, peach palm, ramie, and rubber trees.

Standard K_c and K_{cb} of subtropical orchards and plantations: cactus pear, dragon fruit, fig trees, jujube, passion fruit and pomegranate

This group of fruit crops includes the plants of the cactus family (cactus pear and dragon fruit), which are characterized by a special mode of photosynthesis pathway (Crassulacean Acid Metabolism, CAM) with stomata open at night and that use a temporal CO_2 pump with nocturnal CO_2 uptake and concentration to reduce photorespiration. CAM enables plants to have high adaptability to diverse environments, particularly the ability to tolerate abiotic stresses such as drought and extreme temperatures (Consoli et al. 2013; Kishore 2016). The characteristics of these crops relative to determining K_c and K_{cb} are listed in Table 1.

Cactus pear (*Opuntia ficus-indica* L.), or prickly pear, is a perennial crop used as food and feed, as well as for the cosmetic industry and biofuel production (Elbana et al. 2020). It can be found in semi-arid zones of North and South America, Africa and East Asia. The main cactus pear' producer is Mexico, followed by other South America countries. **Dragon fruit** (*Hylocereus undatus* (Haworth) D.R. Hunt), or pitaya, is a vine-like cactus. The main producer is Vietnam, followed by China and Central American countries.

No previous K_c values tabulation on these crops were available in FAO56 (Allen et al. 1998), and few studies were available in the literature; their characterization (Table 1) was scarce, namely relative to f_c and h. Selected cactus pear plantations refer to a young (Elbana et al. 2020) and a mature plantation (Consoli et al. 2013), while only a study on a young dragon fruit plantation was selected (Batista 2022). A variety of methods was reported for measuring $ET_{c\ act}$ (drainage lysimeters, surface renewal, EC system, and SWB). In all studies, plantations were irrigated using drip or micro-sprinkler irrigation, and full, non-stressed irrigation strategies were adopted. Mild stress was only reported for short periods, thus field conditions correspond to those required for computing standard crop coefficients. Planting densities of cactus pear ranged widely, from 333 to 835 plants/ha. The f_c values of the full bearing cactus, trained with a free form, reached 0.65 while the young plantation had $f_c = 0.35$. The dragon fruit was trained on a trellis system. The actual K_c values obtained from field ET observations are presented in Table 2. The K_c values for the young cactus pears was lower than for the full bearing ones, which relates with the larger f_c of the latter. The K_c values of cactus pear are small ($K_{c\ mid} < 0.50$) and much lower than those of the dragon fruit.

Table 1 Characteristics of cactus pear, dragon fruit, fig trees, jujube, passion fruit and pomegranate plantations and orchards

Author	Cultivar (Rootstock)	Location *Main climate*	ET$_{c\ act}$ field method (ET$_o$ eq.)	Irrig meth *Strategy*	Trees/ha (Spacing, m)	Training system	Age (years)	Height (m)	f$_c$ or f$_{IPAR}$
Cactus pear (*Opuntia ficus-indica* L.)									
Consoli et al. (2013)	Gialla	Sicily, Italy *Med. Semiarid*	SR and EC (ASCE-PM ETo)	Micro-spr *FI*	333 (6×5)	Globe	10 11	3.0	0.65
Elbana et al. (2020)	n/r	Alexandria, Egypt *Med. Semiarid*	SWB-grav (FAO-PM ET$_o$)	Drip *FI*	835 (4×3)	n/r	1–2	n/r	0.35
Dragon fruit (*Hylocereus undatus* (Haworth) D.R. Hunt)									
Batista (2022)	n/r	Rio Grande Norte, BR *Tropical Semiarid, hot*	DL (grass DL ETo)	Trickle *FI*	n/r	n/r	1	2	n/r
Fig tree (*Ficus carica* L.)									
Andrade et al. (2014)	Roxo de Valinhos	Seropédica, RJaneiro, BR *Tropical, humid, hot*	SWB-TDR (FAO-PM-ETo)	Drip *FI, DI*	1667 (3×2)	n/r	3	n/r	n/r
Souza et al. (2014)	Roxo de Valinhos	Botucatu, S.Paulo, BR *Subtrop, subhumid, hot*	SWB-tens (FAO-PM-ETo)	Drip *RDI*	1667 (3×2)	n/r	1	n/r	n/r
Rivera et al. (2016)	Black Mission	Poanas, Durango, MX *Subtrop, hot and dry*	Test K$_c$ values (FAO-PM-ETo)	Drip *RDI*	2000 (2.5×2)	n/r	4	n/r	n/r
Jujube (*Ziziphus jujuba* Mill.)									
Hu et al. (2012)	n/r	Mizhi, Shaanxi, China *Semiarid monsoon*	SWB-FDR (FAO-PM-ET$_o$)	Drip *FI*	1667 (3×2)	n/r	7 8	n/r	n/r
Sun et al. (2012)	n/r	Nanpi, Hebei, China *Semiarid monsoon*	SWB-neutron, SF (FAO-PM-ET$_o$)	Surface *FI*	1111 (4.5×2)	n/r	15 16	n/r	0.67 0.60
Passionfruit (*Passifloraedulis* Sims.) Yellow									
Silva et al. (2006)	IAC 275	Piracicaba, SP, BR *Sub-trop, humid, hot*	WL (FAO-PM-ETo)	Micro-spr *FI*	625 (4×4)	VSP	1–2	1.80	n/r
Souza et al. (2009)	Amarelo Redondo	Vale Curu, Ceara, BR *Trop. Semiarid, hot*	SWB tens (FAO-PM-ETo)	n/r *n/r*	1000 (4×2.5)	n/r	1	n/r	n/r
Freire et al. (2011)	Peroba	Remígio, Paraiba, BR *Trop. Semiarid, hot*	DL (Class A pan)	n/r *FI*	1111 (3×3)	VSP	1	1.65	n/r

Table 1 (continued)

Author	Cultivar (Rootstock)	Location *Main climate*	ET$_{c\ act}$ field method (ET$_o$ eq.)	Irrig meth *Strategy*	Trees/ha (Spacing, m)	Training system	Age (years)	Height (m)	f$_c$ or f$_{IPAR}$
Nogueira et al. (2014)	Amarelo Redondo	Vale Parnaíba, Piauí, BR *Trop. semi-arid, hot*	SWB tens (FAO-PM-ETo)	Drip *FI*	1000 (4×2.5)	VSP	1	1.80	0.16
Macedo et al. (2019)	Guinezinho	Coronel Ezequiel, RGN, BR *Trop. semi-arid, hot*	Test Kc values (Class A pan)	Drip *FI*	555 (3×6)	VSP	1–2	2.20	n/r
Pomegranate (*Punica granatum* L.)									
Bhantana and Lazarovitch (2010)	Wonderful SP-2 (n/r)	Sede Boqer, Israel *Desert*	DL (class A pan ET$_o$)	*n/r FI*	n/r	n/r	1	n/r	n/r
Seidhom and Abd-El-Rahman (2011)	Manfalouty (moderate vig)	North Sinai, Egypt *Subtropical arid*	SWB grav. tens (FAO-PM-ET$_o$)	Drip *FI*	772 (3.6×3.6)	n/r n/r	9	n/r	0.55
Meshram et al. (2012)	n/r	Pune, Maharashtra, India *Semiarid*	K$_c$ from A&P (FAO-PM-ET$_o$)	Drip *n/r*	741 (4.5×3.0)	n/r n/r	1 2 3 4 5	n/r	0.11 0.25 0.62 0.69 0.72
Ayars et al. (2017)	Wonderful (n/r)	Parlier, CA, USA *Med, temp*	WL (FAO-PM-ET$_o$)	SSDrip *FI*	567 (4.9×3.6)	Free form	5	3.0	n/r
Zhang et al. (2017)	Wonderful (n/r)	Kearney, Parlier, CA, USA *Med, temp*	WL, A&P approach (FAO-PM-ET$_o$)	SSDrip *FI*	567 (4.9×3.6)	Free form	2 3 4	3.0	0.25 0.39 0.71
				Drip *FI*	727 (5×2.75)	Vase	2 3 4	3.0	0.17 0.41 0.38
Taha (2018)	Wonderful (n/r)	Alexandria, Egypt *Arid, desert*	SWB-gravim (FAO-PM-ET$_o$)	Drip *FI*	1250 (4×2)	n/r	3	n/r	n/r
Intrigliolo et al. (2019, 2021)	Mollar de Elche (own rooted)	Alicante, Spain *Med*	SF, SWB-capac FAO-PM-ET$_o$)	Drip *FI*	500 (5×4)	Vase	9	3.1	0.56
Niu et al. (2020, 2021)	Wonderful (n/r)	Parlier, CA, USA *Med, temp*	WL (FAO-PM-ET$_o$)	Drip *FI*	727 (5×2.75)	Vase	9	n/r	n/r
Noory et al. (2021)	Malas-e-Saveh (own rooted)	Saveh, Iran *Semiarid, cold winter*	SWB-TDR (FAO-PM-ET$_o$)	Drip *FI*	1481 (4.5×1.5)	n/r	3, 5, 6	n/r	n/r
					1142–893 (3.5×2.5/4×2.8)	n/r	15, 17, 18		
Ramos et al. (2023)	Acco (n/r)	Aljustrel, Portugal *Med*	SWB- SIM-DualKc (FAO-PM-ET$_o$)	Drip *FI*	666 (n/r)	Vase	5–6	2.5	0.41

The **fig** crop (*Ficus carica* L.) is a deciduous tree grown in subtropical/tropical and warm Mediterranean climate areas. Fig trees can bear two fruit harvests in the warm season (Martínez-Macias et al. 2022). No previous standard K$_c$ values were available in FAO56 (Allen et al. 1998). Three related studies were selected (Table 1). Two of the studies were developed in Brazil (Andrade et al. 2014; Souza et al. 2014) and the other in Mexico (Rivera et al. 2016), all measuring $ET_{c\ act}$ with SWB. Plant density ranged from 1666 to 2000 plants/ha. All orchards were drip irrigated, however adopting different irrigation strategies: full irrigation, conventional deficit irrigation and regulated deficit irrigation. Excepting short periods of time, fig trees were reported well irrigated, thus allowing to assume that datasets were appropriate for standard K_c determination.

Jujube (*Ziziphus jujuba* Mill.) is a deciduous fruit tree native to China; its selected studies came from there (Hu et al. 2012; Sun et al. 2012). Jujube thrives in hot and dry areas (Sun et al. 2012). In commercial fields, no specific training systems are required, although pruning is particularly recommended in the first 3 years to promote branching. The selected studies refer to plant populations ranging 1111–1667 plants/ha, measuring ET_c of full bearing jujube orchards (Table 1) with the SWB, to irrigating with drip and surface irrigation and adopting well-watered conditions. Both studies were conducted in fully bearing orchards having a maximum f_c of 0.67. K_c values are medium to high but different between both orchards.

Passion fruit (*Passiflora edulis* Sims.) is an evergreen, fast-growing vine that reach a height of 2.20 m when adopting a trellis system trained in the vertical shoot position (VSP). Planting densities range from 555 to 1111 plants/ha. Brazil is the world's leading producer of passionfruit, followed by other Latin-American countries. All selected studies refer to full-bearing orchards in Brazil, managed under full irrigation conditions and using drip or microsprinkling. $ET_{c\ act}$ was measured with drainage or weighing lysimeters (Silva et al. 2006; Freire et al. 2011), the SWB (Souza et al. 2009; Nogueira et al. 2014) or through testing. The main training system was VSP, with plant heights from 1.65 to 2.2 m and small f_c, similar to vineyards VSP trained. $K_{c\ mid}$ are generally high, up to 1.25.

Pomegranate (*Punica granatum* L.) is a deciduous tree that grows in a variety of climates, from Mediterranean to tropical; India and China are the leading producers. The common training systems are vase and free form (Ayars et al. 2017; Zhang et al. 2017); however, despite that numerous studies were selected, the information about training systems was insufficient. The planting densities varied widely, from 500 to 1481 plants/ha (Table 1). Various $ET_{c\ act}$ measurement methods were reported, namely DL and WL, sap flow and the SWB. Pomegranate water requirements were met adopting full- or eustress irrigation strategies using drip irrigation. Data refers to various crop ages, plant densities, and fraction of ground cover, as well as orchard management; therefore, there is also a wide variation of K_c values but several correspond to standard ones.

Bare soil was the most common soil management of the orchards and plantations of this group (Table 2), although more than 50% of the selected papers do not report information. Only one study is reported for active ground cover (AGC), where SWB data was studied with the SIMDualKc (Rosa et al. 2012a, b), performed an identification of the partition of ET_c between the fruit tree, the AGC vegetation and soil evaporation (Ramos et al. 2023).

$K_{c\ act}$ and $K_{cb\ act}$ values are presented in Table 2 for all crops. Despite the variability and the lack of several data, it has been possible to perceive the dependence of $K_{c\ mid}$ and $K_{cb\ mid}$ from f_c and h, thus the age, as reported by Allen and Pereira (2009) and Pereira et al. (2020b), as well as the training systems adopted. Moreover, it was possible to verify that the four crop growth stages curve was adjustable in all cases, and it was possible to define the proposed K_c and K_{cb} values for the initial, mid-season and end-season, which are presented in Table 3. The $K_{c\ ini}$ values are generally much lower than $K_{c\ mid}$ for deciduous crops due to very low f_c at the initial stage.

Very few information was available in literature relative to basal crop coefficients for those crops, with only two studies using the dual crop coefficient approach, one for jujube (Sun et al. 2012) and the other for pomegranate with the model SIMDualKc (Ramos et al. 2023). Therefore, K_{cb} values were estimated as K_c-0.05 or K_c-0.10 for respectively evergreen and deciduous plants following FAO56 (Allen et al. 1998).

Table 3 was built following the companion papers for fruit tree crops in Mediterranean and temperate climate regions (Pereira et al. 2023; López-Urrea et al. 2024) relating the K_c and/or K_{cb} standard values with the main characteristics of the orchards. These include age (young vs. mature), plant density, f_c and h. Since plant density varies depending on the variety and training system, their range values in Table 3 should be considered as guidelines for users. The values of K_c and K_{cb} for the initial, mid- and end-season were grouped according to the f_c values, plant height and plant density. f_c values range from very low ($f_c < 0.30$) in young plants (non-full bearing) to very high ($f_c > 0.60$) in full bearing orchards or plantations. In cases where few information was available from the selected studies, indicative values for plant density commonly found in commercial orchards and plantations were adopted.

The proposed standard K_{cb} and K_c values are given in the last two columns of Table 3. These standard values were based on the K_{cb} and K_c values obtained from field measurements and proposed in the selected papers (Table 2, reproduced in Table 3) and the ranges of K_c and K_{cb} values previously tabulated in FAO56, Jensen and Allen (2016) and Rallo et al. (2021). This information was additionally combined with the K_{cb} values determined using the A&P approach (Allen and Pereira 2009; Pereira et al. 2020a, b)

Table 2 Field derived crop coefficients of selected cactus pear, dragon fruit, fig trees, jujube, passion fruit and pomegranate plantations and orchards

Author	Cultivar (rootstock)	Training system	f_c or f_{IPAR}	Height (m)	Ground cover	Age	K_c /K_{cb} derived from field observations					
							$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
Cactus Pear (*Opuntia ficus-indica* L.)												
Consoli et al. (2013)	Gialla	Globe	0.65	3.0	n/r	10	n/r	0.48	0.35	n/r	n/r	n/r
						11		0.49	0.26			
Elbana et al. (2020)	n/r	n/r	0.35	n/r	n/r	1–2	0.19	0.19	0.19	n/r	n/r	n/r
Dragon fruit (*Hylocereus undatus* (Haworth) D.R. Hunt)												
Batista (2022)	n/r	n/r	n/r	2	BS	1	0.71	0.77	0.45	n/r	n/r	n/r
Fig tree (*Ficus carica* L.)												
Andrade et al. (2014)	Roxo de Valinhos	n/r	n/r	n/r	n/r	3	n/r	0.70	n/r	n/r	n/r	n/r
Souza et al. (2014)	Roxo de Valinhos	n/r	n/r	n/r	BS	1	0.18	0.49	n/r	n/r	n/r	n/r
					Org Mulch		0.16	0.50				
Rivera et al. (2016)	Black Mission	n/r	n/r	n/r	n/r	4	0.24	1.05	0.35	n/r	n/r	n/r
Jujube (*Ziziphus jujuba* Mill.)												
Hu et al. (2012)	n/r	n/r	n/r	n/r	n/r	7–8	0.50	1.26	0.94	n/r	n/r	n/r
Sun et al. (2012)	n/r	n/r	0.67	n/r	BS	15	0.20	0.80	0.25	n/r	0.50	n/r
			0.60			16						
Passionfruit (*Passiflora edulis* Sims.)												
Silva et al. (2006)	IAC 275	VSP	n/r	1.8	BS	1–2	0.80	1.15	0.80	n/r	n/r	n/r
Souza et al. (2009)	Amarelo Redondo	n/r	n/r	n/r	BS	1	0.65	1.25	n/r	n/r	n/r	n/r
Freire et al. (2011)	Peroba	VSP	n/r	1.65	BS	1	0.64	1.17	n/r	n/r	n/r	n/r
Nogueira et al. (2014)	Amarelo	VSP	0.16	1.8	n/r	1	0.43	1.00	n/r	n/r	n/r	n/r
Macedo et al. (2019)	Guinezinho	VSP	n/r	2.2	n/r	1st y	0.40	1.07	1.02	n/r	n/r	n/r
						2nd y	0.60	1.15	0.90			
Pomegranate (*Punica granatum* L.)												
Bhantana and Lazarovitch (2010)	Wonderful	n/r	n/r	n/r	n/r	1	0.18	0.59	0.20	n/r	n/r	n/r
	SP-2						0.17	0.59	0.28			
Seidhom and Abd-El-Rahman (2011)	Manfalouty	n/r	0.55	n/r	n/r	9	0.39	0.75	0.65	n/r	n/r	n/r
Meshram et al. (2012)	n/r	n/r	0.11	n/r	n/r	1	0.16	0.22	0.25	n/r	n/r	n/r
			0.25			2	0.22	0.48	0.32			
			0.62			3	0.13	1.03	0.69			
			0.69			4	0.14	1.11	0.78			
			0.72			5	0.15	1.14	0.89			
Ayars et al. (2017)	Wonderful	Free form	n/r	3.0	n/r	5	0.30	1.00	0.15	n/r	n/r	n/r
Zhang et al. (2017)	Wonderful	Free form	0.25	3.0	n/r	2	n/r	0.44	n/r	n/r	n/r	n/r
			0.39			3		0.56				
			0.71			4		0.83				
		Vase	0.17	3.0	n/r	2	n/r	0.36	n/r	n/r	n/r	n/r
			0.41			3		0.48				
			0.38			4		0.46				

Table 2 (continued)

Author	Cultivar (rootstock)	Training system	f_c or f_{IPAR}	Height (m)	Ground cover	Age	K_c /K_{cb} derived from field observations					
							$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
Taha (2018)	Wonderful	n/r	n/r	n/r	n/r	3	0.45	1.05	0.75	n/r	n/r	n/r
Intrigliolo et al. (2019)	Mollar de Elche	Vase	0.56	3.1	BS	9	0.31	0.66	0.60	n/r	n/r	n/r
Niu et al. (2020)	Wonderful	Vase	n/r	n/r	BS	9	0.55	0.85	0.35	n/r	n/r	n/r
Noory et al. (2021)	Malas-e-Saveh	n/r	n/r	n/r	BS	3	n/r	0.60	0.20	n/r	n/r	n/r
						5	n/r	0.80	0.30			
						6	n/r	0.85	0.25			
						15	n/r	1.05	0.30	n/r	n/r	n/r
						17	n/r	1.10	0.30			
						18	n/r	1.05	0.30			
Ramos et al. (2023)	Acco	Vase	0.41	2.5	AGC in rainy season	5–6	0.84	0.71	0.84	0.24	0.60	0.52

using the observed f_c and h and the suggested parameters M_L and F_r.

The tabulated standard K_c and K_{cb} values show an increase with the plant density, f_c and height. The dragon fruit, fig tree, jujube, and pomegranate have similar ranges of K_c and K_{cb} for the same f_c. In contrast, cactus pear has lower K_c and K_{cb} values for the same f_c ranges of the other plants because they have a lower ET rate and the F_r parameter is significantly smaller.

Sub-tropical and tropical evergreen fruit trees: cape gooseberry, cherimoya, guava, longan, lychee, mango and papaya orchards

The characteristics of the orchards reported in the selected studies of these crops are summarized in Table 4 and the observed crop coefficients are presented in Table 5.

Cape gooseberry (*Physalis peruviana* L.) is a ground cherry in the nightshade family (Solanaceae), and an edible fruit native to the Amazon rainforest. Main producers are Indonesia and Philippines. It is a perennial plant in the tropics and subtropics. Only a study performed in Brazil (Freitas et al. 2023) was available for the determination of K_c for cape gooseberry (Table 4). The study was performed in a drip irrigated young cape gooseberry orchard with a plant density of 16,666 plants/ha, with average height of 1.80 m; irrigation was performed to fully meet the crop water requirements. The plants were trained in a V-system. $ET_{c\ act}$, was measured using DL and the SWB.

Cherimoya (*Annona cherimola* Mill.) is a fast-growing sub-tropical tree. Spain is a leader in the production of cherimoya fruit, accounting for about 80% of world production (Durán-Zuazo et al. 2019a). The two selected studies (Rodríguez-Pleguezuelo et al. 2011; Durán-Zuazo et al. 2019a), were developed in Spain in the same full bearing orchard, vase-trained and having a plant density of 280 plants/ha. $ET_{c\ act}$ was measured using a DL and performing the SWB. The orchard was drip irrigated adopting full irrigation. (Tables 4 and 5).

Guava (*Psidium guajava* L.) grows in hot and humid tropics, as well as arid tropics, i.e., adapts well to a wide range of warm to hot climates. India and China are the main world producers. The selected studies (Table 4) were developed in Brazil (Teixeira et al. 2003), Cuba (Hernández-Cuello et al. 2015), and India (Singh et al. 2007; Patel and Rajput 2020; Jat et al. 2022). Field measurements of $ET_{c\ act}$ were performed with BREB and SWB, as well as testing different K_c values by comparing the respective crop yield. All studies used drip and micro-sprinkler. The plant density in the studied orchards ranged from 333 to 1000 plants/ha. No information was available regarding the training system and the plants height. Only two studies provided information relative to f_c (0.50–0.66).

Table 3 Proposed initial, mid- and end-season standard K_c and K_{cb} for cactus pear, dragon fruit, fig trees, jujube, passion fruit and pomegranate plantations and orchards as related with the fraction of ground cover and height

Degree of ground cover and plant density	f_c	h (m)	Crop stages	M_L	F_r	Observed values		Previously tabulated		Proposed values	
						K_{cb}	K_c	K_{cb}	K_c	K_{cb}	K_c
Cactus Pear (*Opuntia ficus-indica* L.)											
Young (<3 years)	<0.30	<1.5	Ini	1.0	1.00	–	0.19	–	–	**0.15**	**0.20**
			Mid	1.3	1.00	–	0.19	–	–	**0.20**	**0.25**
			End	1.0	1.00	–	0.19	–	–	**0.20**	**0.25**
Medium (250–300 plants/ha)	0.30–0.50	1.5–2.0	Ini	1.3	0.50	–	–	–	–	**0.20**	**0.30**
			Mid	1.5	0.60	–	–	–	–	**0.30**	**0.40**
			End	1.3	0.60	–	–	–	–	**0.25**	**0.30**
High (>300 plants/ha)	>0.50	>2.0	Ini	1.0	0.50	–	–	–	–	**0.30**	**0.35**
			Mid	2.0	0.55	–	0.48–0.49	–	–	**0.45**	**0.50**
			End	1.1	0.55	–	0.26–0.35	–	–	**0.35**	**0.40**
Dragon fruit (*Hylocereus undatus* (Haworth) D.R. Hunt)											
Young (<3 years)	<0.20	<2.0	Ini	1.1	1.00	–	0.71	–	–	**0.15**	**0.30**
			Mid	1.2	1.00	–	0.77	–	–	**0.25**	**0.40**
			End	1.2	1.00	–	0.45	–	–	**0.25**	**0.40**
Medium (<1800 plants/ha)	0.20–0.30	2.0–2.5	Ini	1.1	0.80	–	–	–	–	**0.25**	**0.40**
			Mid	1.5	1.00	–	–	–	–	**0.50**	**0.65**
			End	1.5	0.80	–	–	–	–	**0.40**	**0.55**
High (>1800 plants/ha)	>0.30	2.0–2.5	Ini	1.3	0.80	–	–	–	–	**0.50**	**0.65**
			Mid	1.6	1.00	–	–	–	–	**0.80**	**0.90**
			End	1.6	0.80	–	–	–	–	**0.60**	**0.75**
High (hedgerow) (>2000 plants/ha)	>0.25	2.0–2.5	Ini	1.3	0.80	–	–	–	–	**0.45**	**0.60**
			Mid	1.5	1.00	–	–	–	–	**0.80**	**0.90**
			End	1.5	0.80	–	–	–	–	**0.55**	**0.70**
Fig tree (*Ficus carica* L.)											
Young (<5 years)	<0.20	<1.5	Ini	1.5	1.00	–	0.16–0.24	–	–	**0.15**	**0.35**
			Mid	1.6	1.00	–	0.50–1.05	0.40	0.45	**0.25**	**0.45**
			End	1.5	1.00	–	0.35	0.25	0.35	**0.15**	**0.35**
Low (<400 plants/ha)	0.20–0.30	1.5–2.0	Ini	1.6	0.65	–	–	–	–	**0.20**	**0.35**
			Mid	1.9	0.85	–	–	–	–	**0.50**	**0.60**
			End	1.6	0.60	–	–	–	–	**0.20**	**0.35**
Medium to high (800–1000 plants/ha)	0.30–0.50	2.0–2.5	Ini	1.6	0.65	–	–	–	–	**0.25**	**0.40**
			Mid	2.0	0.85	–	–	0.60	0.65	**0.75**	**0.80**
			End	1.6	0.60	–	–	0.40	0.45	**0.30**	**0.40**
Jujube (*Ziziphus jujuba* Mill.)											
Young (<3 years)	<0.25	<2.0	Ini	1.2	1.00	–	–	–	–	**0.15**	**0.30**
			Mid	1.3	1.00	–	–	–	–	**0.30**	**0.45**
			End	1.2	1.00	–	–	–	–	**0.20**	**0.35**
Low-Medium (<1100 plants/ha)	0.25–0.40	2.0–3.0	Ini	1.4	0.70	–	–	–	–	**0.20**	**0.35**
			Mid	1.7	0.70	–	–	–	–	**0.45**	**0.55**
			End	1.6	0.60	–	–	–	–	**0.30**	**0.40**
High (>1100 plants/ha)	>0.40	>3.0	Ini	1.4	0.70	–	0.20–0.50	–	–	**0.25**	**0.40**
			Mid	1.8	0.70	0.50	0.80–1.26	–	–	**0.70**	**0.80**
			End	1.7	0.60	–	0.25–0.94	–	–	**0.45**	**0.55**
Passionfruit (*Passiflora edulis* Sims.) Yellow											
Young (<0.5 years) Vertical shoot position (VSP)	<0.15	1.5–2.0	Ini	1.5	1.00	–	–	–	–	**0.25**	**0.45**
			Mid	1.7	1.00	–	–	–	–	**0.30**	**0.50**
			End	1.7	1.00	–	–	–	–	**0.25**	**0.45**

Table 3 (continued)

Degree of ground cover and plant density	f_c	h (m)	Crop stages	M_L	F_r	Observed values		Previously tabulated		Proposed values	
						K_{cb}	K_c	K_{cb}	K_c	K_{cb}	K_c
Medium, VSP (500–700 plants/ha)	0.15–0.35	1.5–2.0	Ini	1.5	0.95	–	0.40–0.80	–	–	**0.45**	**0.60**
			Mid	2.0	1.00	–	1.07–1.15	–	–	**0.60**	**0.75**
			End	2.0	0.95	–	0.80–1.02	–	–	**0.50**	**0.65**
High, VSP (1000 plants/ha)	0.35–0.45	1.5–2.0	Ini	1.5	0.95	–	0.43–0.65	–	–	**0.70**	**0.85**
			Mid	2.0	1.00	–	1.00–1.25	–	–	**0.85**	**1.00**
			End	2.0	0.95	–	0.80	–	–	**0.75**	**0.85**
Young, hedgerow	<0.35	1.5–2.0	Ini	1.5	1.00	–	–	–	–	**0.50**	**0.60**
			Mid	1.7	1.00	–	–	–	–	**0.60**	**0.65**
			End	1.7	1.00	–	–	–	–	**0.55**	**0.65**
High, hedgerow (1000 plants/ha)	>0.35	1.5–2.0	Ini	1.5	0.95	–	–	–	–	**0.80**	**0.90**
			Mid	2.0	1.00	–	–	–	–	**0.95**	**1.00**
			End	2.0	0.95	–	–	–	–	**0.80**	**0.90**
Young, overhead trellis	<0.60	1.8–2.2	Ini	1.4	1.00	–	–	–	–	**0.60**	**0.70**
			Mid	1.6	1.00	–	–	–	–	**0.75**	**0.80**
			End	1.6	1.00	–	–	–	–	**0.70**	**0.75**
Very high, overhead trellis (2000 plants/ha)	>0.60	1.8–2.2	Ini	1.5	0.95	–	–	–	–	**0.95**	**1.00**
			Mid	2.0	1.00	–	–	–	–	**1.00**	**1.05**
			End	2.0	0.95	–	–	–	–	**0.95**	**1.00**
Pomegranate (*Punica granatum* L.)											
Young (<5 years)	<0.25	<2.0	Ini	1.1	1.00	–	0.16–0.18	–	–	**0.15**	**0.30**
			Mid	1.3	1.00	–	0.22–0.60	0.30–0.35	0.35–0.40	**0.30**	**0.40**
			End	1.3	1.00	–	0.20–0.28	0.20–0.25	0.30–0.35	**0.20**	**0.30**
Low, vase (500–800 plants/ha)	0.25–0.40	2.0–2.5	Ini	1.4	0.85	–	0.22–0.45	–	–	**0.20**	**0.35**
			Mid	1.5	0.75	–	0.44–1.05	0.45–0.50	0.50–0.55	**0.45**	**0.55**
			End	1.5	0.55	–	0.30–0.75	0.30–0.35	0.40–0.45	**0.25**	**0.35**
Medium, vase (500–800 plants/ha)	0.40–0.60	2.5–3.0	Ini	1.4	0.85	0.24	0.30–0.84	–	–	**0.30**	**0.45**
			Mid	1.5	0.75	0.60	0.48–1.00	0.55–0.90	0.60–0.95	**0.65**	**0.70**
			End	1.5	0.55	0.52	0.15–0.84	0.40–0.60	0.45–0.65	**0.35**	**0.45**
High, vase (>800 plants/ha)	>0.60	>3.0	Ini	1.4	0.85	–	0.13–0.55	–	–	**0.35**	**0.45**
			Mid	1.8	0.75	–	0.83–1.14	–	–	**0.85**	**0.90**
			End	1.8	0.55	–	0.30–0.89	–	–	**0.50**	**0.60**

Longan (*Dimocarpus longan* Lour.) belongs to the Sapindaceae family, as lychee, and is mainly cultivated in subtropical regions, with China being the largest producer, followed by Thailand. Only one study was available which was developed in Thailand (Suwanlertcharoen et al. 2023). The study used the METRIC energy balance model coupled with SIMDualKc water balance model for the estimation of $ET_{c\ act}$. The study lacks detailed information on the studied orchards.

Lychee (*Litchi chinensis* Sonn.) is cultivated in the limits of tropical and subtropical climates, mainly in Asia. The crop is mainly cultivated in China (600,000 ha), followed by India, Thailand and Vietnam. The available studies on the determination of K_c (Table 4) were carried out in the main growing countries (India and Thailand), two of them in full bearing orchards (Spohrer et al. 2006; Mali et al. 2015) and one study was carried out in a young orchard (Tiwari et al. 2012). The methods used to estimate the $ET_{c\ act}$ were the sap flow to assess $T_{c,}$ thus determining K_{cb}, and testing successive K_c values relating the resulting ET with the crop yield. The irrigation was applied for fulfilling the crop water requirements using drip irrigation. The plant density ranged from 100 to 400 plants/ha. Few information was available relative to f_c and h.

Mango (*Mangifera indica* L.) is native to southern Asia but is widespread throughout the tropical and subtropical regions of the world. India is the leading producer of mango. The selected studies in Table 4 were performed in full bearing orchards of the subtropical Mediterranean climate in Spain (Rodríguez-Pleguezuelo et al. 2011; Durán-Zuazo

Table 4 Characteristics of selected cape gooseberry, cherimoya, guava, lychee, mango and papaya orchards

Author	Cultivar (rootstock)	Location & *main climate*	Method $ET_{c\ act}$ (ET_o equation)	Irrig method *strategy*	Trees/ha (Spacing, m)	Training system	Age (years)	Height (m)	f_c or f_{IPAR}
Cape gooseberry (*Physalis peruviana* L.)									
Freitas et al (2023)	n/r	Viçosa, Min-Gerais BR, Trop hot	DL, SWB (FAO-PM ET_o)	Drip FI	4200 (n/r)	V system	1–2	1.8	n/r
Cherimoya (*Annona cherimola* Mill.)									
Rodríguez-Pleguezuelo et al. (2011)	Fino de Jete	Granada coast, Spain *Subtropical Med*	DL, SWB-FDR (FAO-PM ET_o)	Drip *FI*	280 (7 × 5)	Vase	15	n/r	n/r
Durán-Zuazo et al. (2019a)	Fino de Jete	Granada coast, Spain *Subtropical Med*	DL, SWB-FDR (FAO-PM ET_o)	Drip *FI*	280 (7 × 5)	Vase	20	n/r	n/r
Guava (*Psidium guajava* L.)									
Teixeira et al. (2003)	Paluma (n/r)	Petrolina, Brazil *Trop. Semi-arid hot*	BREB (FAO-PM ET_o)	Mic-spr *FI*	333 (6 × 5)	n/r	2	n/r	n/r
Singh et al. (2007)	KG/KAJI (n/r)	Kharagpur, Bengal, Ind *Subtrop. Hot, humid*	Test K_c-yield (FAO-PM ET_o)	Drip *FI*	400 (5 × 5)	n/r	n/r	n/r	0.50
Hernández-Cuello et al. (2015)	Enana Roja (EEA 18–40 dwarf)	La Habana, Cuba *Trop. Hot and humid*	SWB-gravtens (FAO-PM ET_o)	Drip *FI*	1000 (5 × 2)	n/r	n/r	n/r	0.66
Patel and Rajput (2020)	Allahabad Safeda	New-Delhi, India *Tropical hot humid*	Test K_c-yield (FAO-PM ET_o)	Drip *FI*	400 (5 × 5)	n/r	Mature	n/r	n/r
Jat et al. (2022)	VNR Bihi (wedge grafted)	Uttarakhand, India *Subtrop warm, humid*	Test K_c (pan evap ET_o)	Drip	600 (5 × 3)	n/r	5	n/r	n/r
Longan (*Dimocarpus longan* Lour.)									
Suwanlertcharoen et al. (2023)	n/r	Chiang Mai Province, Tailand *Subtrop warm, humid*	METRIC, SIMDualKc (ASCE-PM ET_r)	n/r	n/r	n/r	n/r	n/r	n/r
Lychee (*Litchi chinensis* Sonn.)									
Spohrer et al. (2006)	n/r	Chiang Mai, Thailand *Trop warm wet*	SF (FAO-PM-ET_o)	n/r n/r	100 (10.0 × 10.0)	n/r	7	n/r	0.22
Tiwari et al. (2012)	Ata Bombai (n.a)	Kharagpur, India *Trop warm wet*	Test K_c (FAO-PM-ET_o)	Drip *FI*	400 (5.0 × 5.0)	n/r	2	4.1	n/r

Table 4 (continued)

Author	Cultivar (rootstock)	Location & *main climate*	Method $ET_{c\ act}$ (ET_o equation)	Irrig method *strategy*	Trees/ha (Spacing, m)	Training system	Age (years)	Height (m)	f_c or f_{IPAR}
Mali et al. (2015)	Shahi (n.a)	Ranchi, Jharkhand India *Trop. Warm wet*	Test Kc (ClassApan ET_o)	Drip *FI*	100 (10.0×10.0)	n/r	26	n/r	n/r
Mango (*Mangifera indica* L.)									
Silva et al. (2007)	Tommy Atkins (n/r)	Petrolina, Brazil *Trop. Semi-arid*	BREB, SWB (FAO-PM ET_o)	Drip *FI*	250 (8×5)	n/r	7–8	5.2	n/r
Mattar (2007)	Zebda (n/r)	El-Sharkya, Egypt *Arid. Hot and dry*	SWB- grav (FAO-PM ET_o)	Drip, Surf. *FI*	400 (5×5)	n/r	5	2.2–2.7	n/r
Teixeira et al. (2008)	Tommy Atkins (n/r)	Petrolina, Brazil *Trop. Semi-arid*	EC (FAO-PM ET_o)	Micro-spr. *FI*	100 (10×10)	n/r	18–19	5.5	n/r
Rodríguez-Pleguezuelo et al. (2011)	Osteen (n/r)	Almuñécar, Granada ES *Subtropical Med*	DL (FAO-PM ET_o)	Drip *FI*	600 (5.5×3)	Vase	15	n/r	n/r
Mohammad et al. (2015)	n/r	Jazan, Saudi Arabia *Trop. Semi-arid*	SWB-tens (ASCE-PM ET_o)	Drip *FI*	156 (8×8)	n/r	Mature	n/r	n/r
Durán-Zuazo et al. (2019b)	Osteen (Gomera-1)	Almuñécar, Granada ES *Subtropical Med*	DL (FAO-PM ET_o)	Drip *FI*	600–630 (5.5×3)	n/r	15	2.9	0.44
Papaya (*Carica papaya* L.)									
Montenegro et al. (2004)	Sunrise Solo	Paraipaba, Ceará, BR *Trop. Hot and wet*	SWB-tens (FAO-PM ET_o)	Mic-spr *FI*	1333 (3.5×2.5)	n/r	1	n/r	n/r
Coelho et al. (2010)	Sunrise Solo	Cruz das Almas, Baía BR *Trop. Hot and humid*	Test K_c value (FAO-PM ET_o)	Drip *FI*	1960 (3.4×1.5)	n/r	1–2	2.15	n/r
Chaterlán et al. (2012a, b)	Maradol Roja	Alquizar, Habana, CU *Trop. Hot and wet*	SWB -ISAREG & SIMDualKc (FAO-PM ET_o)	Drip *FI*	1851 (3.6×1.5)	n/r	Mature	3.0	0.82

et al. 2019b) and the tropical semi-arid and arid climates of northeast Brazil (Silva et al. 2007; Teixeira et al. 2008), North Africa (Mattar 2007) and Saudi Arabia (Mohammad et al. 2015). SWB was the most used method for measuring $ET_{c\ act}$. The orchards were mainly drip irrigated but one study used furrow irrigation. The planting density varied from 100 to 630 plants/ha. Only a single study reported a f_c value of 0.44. The plant height of some dwarf or semi-dwarf

Table 5 Field derived crop coefficients of selected cape gooseberry, cherimoya, guava, lychee, mango and papaya orchards

Author	Cultivar (rootstock)	Training system	f_c or f_{IPAR}	Height (m)	Ground cover	Age	K_c /K_{cb} derived from field observations					
							$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
Cape gooseberry (*Physalis peruviana* L.)												
Freitas et al (2023)	n/r	V sys	n/r	1.81	BS	1–2	0.45	1.35	0.48	0.18	0.96	0.26
Cherimoya (*Annona cherimola* Mill.)												
Rodríguez-Pleguezuelo et al. (2011)	Fino de Jete	Vase	n/r	n/r	BS	15	n/r	0.65	0.15	n/r	n/r	n/r
Durán-Zuazo et al. (2019a)	Fino de Jete	Vase	n/r	n/r	BS	20	0.10	0.60	0.15	n/r	n/r	n/r
Guava (*Psidium guajava* L.)												
Teixeira et al. (2003)	Paluma	n/r	n/r	n/r	n/r	2	n/r	0.85	0.75	n/r	n/r	n/r
Singh et al. (2007)	KG/KAJI	n/r	0.50	n/r	Pl mulch	n/r	0.60	0.72	0.55	n/r	n/r	n/r
Hernández-Cuello et al. (2015)	Enana roja (EEA18-40)	n/r	0.66	n/r	n/r	n/r	0.55	1.25	0.45	n/r	n/r	n/r
Patel and Rajput (2020)	Allahabad Safeda	n/r	n/r	n/r	n/r	Mature	0.65	0.80	n/r	n/r	n/r	n/r
Jat et al. (2022)	VNR Bihi	n/r	n/r	n/r	BS	5	n/r	0.80	n/r	n/r	n/r	n/r
Longan (*Dimocarpus longan* Lour.)												
Suwanlertcharoen et al. (2023)	n/r	n/r	n/r	n/r	n/r	n/r	0.67	0.86	0.52	n/r	n/r	n/r
Lychee (*Litchi chinensis* Sonn.)												
Spohrer et al. (2006)	n/r	n/r	0.22	n/r	n/r	7	n/r	n/r	n/r	0.46	0.80	n/r
Tiwari et al. (2012)	Ata Bombai	n/r	n/r	4.1	Pl mulch	2	0.56	0.62	0.60	n/r	n/r	n/r
Mali et al. (2015)	Shahi	n/r	n/r	n/r	n/r	26	0.85	0.85	0.85	n/r	n/r	n/r
Mango (*Mangifera indica* L.)												
Silva et al. (2007)	Tommy Atkins	n/r	n/r	5.2	n/r	7–8	n/r	0.84	n/r	n/r	n/r	n/r
Mattar (2007)	Zebda	n/r	n/r	2.7 2.4 2.2	BS	5	0.60 0.65 0.75	0.85 0.93 1.12	0.60 0.65 0.70	n/r	n/r	n/r
Teixeira et al. (2008)	Tommy Atkins (n/r)	n/r	n/r	5.5	BS	18 19	0.70 0.75	1.10 1.00	0.93 0.65	0.45 0.41	0.85 0.75	0.71 0.44
Rodríguez-Pleguezuelo et al. (2011)	Osteen (Gomera-1)	n/r	n/r	n/r	BS	15	0.35	0.75	0.20	n/r	n/r	n/r
Mohammad et al. (2015)	n/r	n/r	n/r	n/r	n/r	Mature	0.71	0.77	0.73	n/r	n/r	n/r
Durán-Zuazo et al. (2019b)	Osteen (Gomera-1)	n/r	0.44	2.9	BS	15	0.40	0.80	0.25	n/r	n/r	n/r
Papaya (*Carica papaya* L.)												
Montenegro et al. (2004)	Sunrise Solo	n/r	n/r	n/r	n/r	1	0.54	0.89	n/r	n/r	n/r	n/r
Coelho et al. (2010)	Sunrise Solo	n/r	n/r	2.2	n/r	1–2	0.31 0.38	0.84 1.02	n/r	n/r	n/r	n/r
Chaterlán et al. (2012a/b)	Maradol Roja	n/r	0.82	3.0	BS	Mature	0.90	1.10	0.90	0.15	1.00	0.60

cultivars reaches only 2.5–4.0 m but the selected studies referred heights from 2.2 to 5.5 m.

Papaya *(Carica papaya* L.) is mainly cropped in India followed by Brazil, Indonesia, and Mexico. The period between planting and harvesting is generally around 9 months and commercial orchards last around 3–10 years. In the north-eastern region of Brazil, where two of the selected studies were conducted (Montenegro et al. 2004; Coelho et al. 2010), papaya trees are often in consociation with other perennial fruits that require a partially shaded environment, such as dwarf coconut and cacao. Table 4 presents the characteristics of the selected studies on papaya orchards with all orchards being full bearing. The measurement of $ET_{c\ act}$ was performed mainly using the SWB. In one of the studies, performed in Cuba, the SIMDualKc model was used to partition crop ET into plant transpiration and soil evaporation (Chaterlán et al. , 2012b). All orchards were full irrigated with micro-irrigation systems. Plant cultivation is mainly done in single-row orchards with a density of 1000–2000 plants/ha, but there are also double-row spacing. The papaya height ranged from 2.15 to 3.0 m, with f_c attaining values as high as 0.82 in a mature orchard.

Table 5 presents the values of K_c and K_{cb} reported in the selected studies for all crops of this item together with factors that mainly influence them: plant density, f_c, and h. The observation of results lets perceive and confirm the importance of these and their association with specific cultivation practices such as the training system, and soil management. Few information was provided on row and inter-row ground cover, but most studies were conducted under bare soil (BS) conditions. Pruning practices were not reported in the selected studies, and therefore, their impacts could not be assessed. The training system was only reported on the studies of cape gooseberry and cherimoya, which, together with the plant density, determine the crop height and the fraction of ground cover, that have a great influence on the K_c/K_{cb} values. The data on f_c and h was also limited, thus not allowing to adequately characterize the orchards and plantations.

The $K_{c\ ini}$ values are around 0.50–0.60 for most crops, reflecting lower vegetative development (i.e., lower K_{cb} values) and higher evaporation from the soil due to frequent soil wetting events from precipitation and irrigation. Generally, much higher K_c values were observed during the mid-season, exceeding 1.0 in some cases when, due to the high contribution of soil evaporation during the wet season.

Following the same approach as for Table 3, Table 6 was built relating the K_c and K_{cb} standard values for the initial, mid- and end-season stages, with the main characteristics of the orchards, i.e., age (young vs. full bearing or mature), plant density and the related fraction of ground cover and plants hight. The degree of ground cover or f_c varies from very low in young (non-full bearing) plants (<1–8 years, depending on the crop) to very high. Plant densities and f_c values presented in Table 6 should be viewed as indicative of what is commonly found in commercial orchards. The described groups may help users to decide which group is more suitable for the case under study. The information relative to f_c and h can be used along with the proposed parameters M_L and F_r to compute the K_{cb} values using the A&P approach (Allen and Pereira 2009; Pereira et al. 2020a).

Table 6 also presents the ranges of K_{cb} and K_c obtained from field measurements and proposed in the selected studies and the ranges of K_c and K_{cb} values previously tabulated for cherimoya, guava, mango, and papaya (Allen and Pereira 2009; Rallo et al. 2021). Readers are advised to interpolate the proposed K_{cb} and K_c using their available data.

Tropical evergreen orchards and plantations: acerola, carambola, cashew, cacao, coffee, jaboticaba, jatropha, macadamia

The main characteristics of the crops in this section originated from the selected studies presented in the following and summarized in Table 7. The observed K_c and K_{cb} values are presented in Table 8.

Acerola (*Malpighia emarginata* DC.), or Barbados cherry, is a shrub or small tree (2–3 m). Brazil is the world's largest producer, and the production area has increased in recent years. However, there is a lack of studies focusing on water use and determining crop coefficients. The two selected studies (Konrad 2002; Santos et al. 2014) were developed in the southeastern region of Brazil (Table 7). Both were performed in young acerola orchards and $ET_{c\ act}$ was measured using a weighing lysimeter (Santos et al. 2014). In the other study, an estimation test of different K_c values impacts on yields was used (Konrad 2002). The latter orchard was irrigated using micro-sprinklers and the former used drip irrigation. The plant density generally ranges from 416 to 833 plants/ha (Ritzinger and Ritzinger 2011) and the study by Konrad (2002) reported a plant density of 666 plants/ha. None of the selected studies reported on f_c or h and only the mid-season K_c values were proposed, 0.88–1.00 (Table 8).

Carambola (*Averrhoa carambola* L.), also called star fruit, is mainly grown in Southeast Asia and is widely cultivated in tropical and subtropical warm areas. The largest world's producer is Malaysia. Carambola is sensitive to temperatures below 10 °C, particularly the young trees, and high wind speed. There was only one study available for this crop (Kisekka et al. 2010), which was developed in USA in a mature orchard. $ET_{c\ act}$ was measured with the SWB. The orchard had a plant density of 494 plants/ha, was irrigated using micro-sprinkler and a full irrigation strategy was adopted. The reported K_c values were high, with $K_{c\ ini} = 1.00$ and $K_{c\ mid} = 1.15$ (Table 8).

Table 6 Initial, mid- and end-season standard single and basal crop coefficients for cape gooseberry, cherimoya, guava, lychee, mango and papaya orchards as related with the fraction of ground cover and height

Degree of ground cover/training	f_c	h		M_L	F_r	Field reported values		Previously tabulated		Proposed values	
						K_{cb}	K_c	K_{cb}	K_c	K_{cb}	K_c
Cape gooseberry (*Physalis peruviana* L.)											
Young (<5 years)	<0.30	<1.0	Ini	1.2	1.00	0.18	0.45	–	–	**0.25**	**0.45**
			Mid	1.5	1.00	0.96	1.35	–	–	**0.40**	**0.50**
			End	1.5	1.00	0.26	0.48	–	–	**0.30**	**0.40**
Common density (<7000 plants/ha)	0.30–0.50	1.0–2.0	Ini	1.5	0.60	–	–	–	–	**0.35**	**0.55**
			Mid	2.0	1.00	–	–	–	–	**0.85**	**0.95**
			End	2.0	0.65	–	–	–	–	**0.50**	**0.65**
Cherimoya (*Annona cherimola* Mill.)											
Young (<3 years)	<0.15	<1.5	Ini	1.0	1.00	–	–	–	–	**0.15**	**0.35**
			Mid	1.4	1.00	–	–	–	–	**0.25**	**0.45**
			End	1.4	1.00	–	–	–	–	**0.20**	**0.40**
Low – Medium (125–400 plants/ha)	0.15–0.35	1.5–3.5	Ini	1.6	0.70	–	0.10	–	–	**0.30**	**0.45**
			Mid	1.7	0.85	–	0.60–0.65	–	–	**0.45**	**0.60**
			End	1.7	0.75	–	0.15	–	–	**0.40**	**0.50**
Medium–High (500–1250 plants/ha)	>0.35	>3.0	Ini	1.8	0.70	–	–	–	–	**0.55**	**0.65**
			Mid	1.9	0.85	–	–	–	–	**0.80**	**0.85**
			End	1.9	0.75	–	–	–	–	**0.65**	**0.70**
Guava (*Psidium guajava* L.)											
Young (<8 years)	<0.20	<1.5	Ini	1.2	1.00	–	–	–	–	**0.15**	**0.40**
			Mid	1.4	1.00	–	–	–	–	**0.30**	**0.45**
			End	1.4	1.00	–	–	–	–	**0.25**	**0.50**
Low-Medium (<300 plants/ha)	0.20–0.40	1.5–2.0	Ini	1.8	0.75	–	0.60	–	–	**0.40**	**0.60**
			Mid	2.0	0.85	–	0.72	–	–	**0.60**	**0.75**
			End	2.0	0.80	–	0.55	–	–	**0.55**	**0.70**
High (<350 plants/ha)	0.40–0.60	2.0–2.5	Ini	1.8	0.75	–	0.60	–	–	**0.65**	**0.75**
			Mid	2.0	0.85	–	0.72	–	–	**0.85**	**0.90**
			End	2.0	0.80	–	0.55	–	–	**0.80**	**0.85**
Very High (> 300 plants/ha)	>0.60	>2.5	Ini	1.8	0.75	–	0.55	–	–	**0.80**	**0.90**
			Mid	2.0	0.85	–	1.25	–	–	**0.90**	**1.05**
			End	2.0	0.80	–	0.45	–	–	**0.85**	**1.00**
Longan (*Dimocarpus longan* Lour.)											
Young (<5 years)	<0.30	1.0–2.0	Ini	1.5	1.00	–	–	–	–	**0.30**	**0.50**
			Mid	1.6	1.00	–	–	–	–	**0.45**	**0.60**
			End	1.6	1.00	–	–	–	–	**0.45**	**0.60**
Common density (250–300 plants/ha)	>0.30	2.5–4.0	Ini	1.9	0.80	0.67	–	–	–	**0.70**	**0.80**
			Mid	2.0	0.90	0.86	–	–	–	**0.90**	**0.95**
			End	2.0	0.90	0.52	–	–	–	**0.85**	**0.90**
Lychee (*Litchi chinensis* Sonn.)											
Young (<5 years), vase	<0.20	<2.5	Ini	1.5	1.00	–	0.56			**0.35**	**0.55**
			Mid	1.6	1.00	–	0.62			**0.40**	**0.60**
			End	1.6	1.00	–	0.60			**0.40**	**0.60**
Low-Medium, vase (100–200 plants/ha)	0.20–0.30	2.5–4.0	Ini	1.9	0.80	0.46	–			**0.45**	**0.65**
			Mid	2.0	0.90	0.80	–			**0.60**	**0.75**
			End	2.0	0.90	–	–			**0.55**	**0.70**
High, vase (200–400 plants/ha)	>0.30	>4.0	Ini	1.9	0.80	–	0.85			**0.70**	**0.80**
			Mid	2.0	0.90	–	0.85			**0.90**	**1.00**
			End	2.0	0.90	–	0.85			**0.80**	**0.95**

Table 6 (continued)

Degree of ground cover/training	f_c	h		M_L	F_r	Field reported values		Previously tabulated		Proposed values	
						K_{cb}	K_c	K_{cb}	K_c	K_{cb}	K_c
Mango (*Mangifera indica* L.)											
Young (<4 years)	<0.25	<2.0	Ini	1.4	1.00	–	–	–	–	**0.25**	**0.45**
			Mid	1.6	1.00	–	–	–	–	**0.40**	**0.60**
			End	1.6	1.00	–	–	–	–	**0.35**	**0.65**
Low-Medium (100–250 plants/ha)	0.25–0.40	2.0–3.0	Ini	1.7	0.75	–	0.60–0.75	0.20	0.30	**0.45**	**0.60**
			Mid	2.0	0.85	–	0.85–1.12	0.40	0.45	**0.70**	**0.85**
			End	2.0	0.80	–	0.60–0.70	0.35	0.40	**0.60**	**0.75**
High (400–600 plants/ha)	0.40–0.50	2.5–4.0	Ini	1.7	0.75	0.41–0.45	0.35–0.75	0.25	0.35	**0.65**	**0.75**
			Mid	2.0	0.85	0.75–0.85	0.75–1.10	0.70	0.75	**0.85**	**0.95**
			End	2.0	0.80	0.44–0.71	0.20–0.93	0.55	0.60	**0.75**	**0.85**
Papaya (*Carica papaya* L.)											
Young (<1 year)	<0.40	<1.5	Ini	1.2	1.00	–	0.54	–	–	**0.35**	**0.50**
			Mid	1.6	1.00	–	0.89	–	–	**0.60**	**0.75**
			End	1.6	1.00	–	–	–	–	**0.55**	**0.55**
Medium (single row) (1330–4500 plants/ha)	0.40–0.70	1.5–3.0	Ini	1.3	0.70	–	0.31–0.38	–	–	**0.55**	**0.65**
			Mid	1.5	0.90	–	0.84–1.02	–	–	**0.85**	**0.95**
			End	1.5	0.70	–	–	–	–	**0.60**	**0.70**
High (single or double row) (<7000 plants/ha)	0.70–0.85	>2.5	Ini	1.5	0.70	0.15	0.90	–	–	**0.75**	**0.80**
			Mid	1.7	0.90	1.00	1.10	–	–	**1.00**	**1.05**
			End	1.7	0.70	0.60	0.90	–	–	**0.80**	**0.85**

Cashew (*Anacardium occidentale* L.) is a tropical tree originated in northeast Brazil, but is mainly grown in Côte d'Ivoire and India. Cashew orchards are commonly rainfed, and no grafting and training systems are used, resulting in low productivity (Carneiro et al. 2004). Common cashew cultivars can reach a height of 5–8 m, while new cultivars are early maturity and dwarf plants for easy harvesting (Gondim et al. 2020). New dwarf cashew cultivars are full bearing after two years of planting. The selected studies focused on these early-maturity dwarf cultivars developed in Brazil. One study was developed in a young orchard (Gondim et al. 2020), and the other was carried out along five years in the same orchard (Miranda et al. 2013). In both studies, measurements of $ET_{c\ act}$ were performed with SWB. Micro-irrigation was used, and the plant density ranged from 180 to 312 plants/ha. The information on f_c was provided in a five years study (Miranda et al. 2013), showing f_c ranging 0.05–0.65. According to the study by Miranda et al. (2013), the K_c values are quite similar along the year (Table 8), ranging from 0.50 to 0.65, according to the orchard development, i.e., to the f_c. The study by Gondim et al. (2020) presented a wide K_c range, from 0.30 to 0.87 (Table 8).

Cacao (*Theobroma cacao* L.) is an evergreen tree native to the Amazon basin but Côte d'Ivoire and Ghana are the largest cacao producing countries. Cacao is commonly grown in shade, although high yields have been observed in full sun monocultures (Baligar et al. 2008). Pruning is not a common practice in most cacao orchards. Three studies were selected from the literature, two of them developed in fully bearing orchards, one in Mexico (López-López et al. 2013) and the other in Brazil (Waldburger et al. 2019), the other in Indonesia, likely mature but without information on age (Kaimuddin et al. 2020). $ET_{c\ act}$ was measured using the SWB and, in one case, with crop transpiration measurements using sap flow sensors. However, only Waldburger et al. (2019) provided for an adequate set of information. This orchard was drip irrigated and had a plant density of 1250 plants/ha, which is within the commonly used ranges of 1096–3333 plants/ha (Carr and Lockwood 2011). The mean plant height was 3 m. The K_c values ranged from 0.60–1.04, 0.70–1.04 and 0.70–1.04 for the initial, mid-season and end-season stages, respectively (Table 8). The results show that K_c values are relatively similar throughout the season in the same orchard.

Coffee (*Coffea arabica* L.) and *Coffea canephora* (var. *robusta*) are the two main grown varieties. The specie arabica accounts for 70% of global coffee production. Brazil is the main producer. Most of the selected studies were developed in Brazil (Silva et al. 2009; Lena et al. 2011, Vale Sant'Ana et al. 2022) while one was developed in Colombia (Castaño-Marín et al. 2021). The measurement of $ET_{c\ act}$ was performed using diverse methods, with the

Table 7 Characteristics of selected acerola, carambola, cashew, cacao, coffee, jaboticaba, jatropha, macadamia orchards

Author	Cultivar (rootstock)	Location & *main climate*	Field method for $ET_{c\ act}$ (ET_o equation)	Irrigation method & *strategy*	Trees/ha (Spacing, m)	Training system	Age (years)	Height (m)	f_c or f_{IPAR}
Acerola (*Malpighia emarginata* DC.)									
Konrad (2002)	Oliver	Junqueirópolis, S.Paulo BR *Subtrop humid, warm*	Test Kc-yield (FAO-PM ET_o)	Micro-spr, *SSDI*	666 (5.0 × 3.0)	n/r	3	n/r	n/r
Santos et al. (2014)	n/r	Cruz das Almas, BA, BR *Subtrop humid hot*	WL (FAO-PM ET_o)	n/r	n/r	n/r	2	n/r	n/r
Carambola (*Averrhoa carambola* L.)									
Kisekka et al. (2010)	Arkin	Homestead, FL USA *Subtrop humid warm*	SWB-tens (ASCE-EWRI)	Micro-spr *FI*	494 (4.5 × 4.5)	n/r	15	n/r	n/r
Cashew (*Anacardium occidentale* L.), early maturity dwarf									
Miranda et al. (2013)	n/r	Paraipaba, Ceará, BR *Tropical Hot and dry*	SWB-tens (FAO-PM ET_o)	Micro-spr, Drip *FI*	180 (8 × 7)	n/r	1–5	n/r	0.05–0.65
Gondim et al. (2020)	BRS 266	Paraipaba, Ceará, BR *Tropical Hot and dry*	SWB (FAO-PM ET_o)	n/r	312 (8 × 4)	n/r	1	0.72	n/r
Cacao (*Theobroma cacao* L.)									
López-López et al. (2013)	INIFAP F-7 hybrid	Huimanguillo, Tabasco MX *Tropical humid, hot*	SF, SWB (ETo-pan)	n/r *DI*	n/r	n/r	10	n/r	n/r
Waldburger et al. (2019)	CCN51	Juazeiro, Bahia, Brazil *Tropical Hot and dry*	SWB-sensor (FAO-PM ET_o)	Drip *FI*	1250 (2 × 4)	vase	4–7	3	n/r
Kaimuddin et al. (2020)	n/r	Luwu, Sulawesi Indonesia *Tropical humid, warm*	Cropwat 8.0 (FAO-PM ET_o)	n/r	n/r	n/r	n/r	n/r	n/r
Coffee (*Coffea arabica* L.)									
Silva et al. (2009)	IAC-44	Piracicaba, S. Paulo, BR *Tropical hot&humid*	SWB – neutron (FAO-PM ET_o))	n/r *FI*	7619 (1.75 × 0.75)	n/r	3–4	n/r	n/r

Table 7 (continued)

Author	Cultivar (rootstock)	Location & *main climate*	Field method for $ET_{c\ act}$ (ET_o equation)	Irrigation method & *strategy*	Trees/ha (Spacing, m)	Training system	Age (years)	Height (m)	f_c or f_{IPAR}
Lena et al. (2011)	Iapar 59	Londrina, Paraná, BR *Subtrop. Humid, warm*	WL (n/r)	Sprink, Drip *FI*	3125 (2.0×1.6)	n/r	5–6	n/r	n/r
Pereira et al. (2011)	IAC388-17 (Apoatã IAC 2258)	Piracicaba, S. Paulo, BR *Trop. Hot, humid*	SWB-gravim. (Class A pan)	Sprinkler *FI*	4000 (2.5×1.0)	n/r	2–4	n/r	n/r
Castaño-Marín et al. (2021)	Castillo Paraguaicito	Buenavista, Quindío, CO *Trop. Humid and warm*	EC (FAO-PM ET_o)	Rainfed	7143 (1.4×1.0)	n/r	1–4	n/r	n/r
Vale Sant'Ana et al. (2022)	Catiguá MG-3	Lavras, Minas Gerais, BR *Trop. Hot humid*	SWB- tensiom (FAO-PM ET_o)	DI *FI*	6666 (2.5×0.6)	n/r	2–6	2.09	n/r
Jaboticaba (*Plinia peruviana* (Poir.) Govaerts)									
Bergamaschi and Prua (2018)	n/r	Porto Alegre, RGSul, BR *Sub-trop. Humid temperate*	SWB-TDR (FAO-PM-ET_o)	Rainfed	494 (4.5×4.5)	n/r	10–12	3.5	0.80
Jatropha (*Jatropha curcas* L.)									
Garg et al. (2014)	n/r	Andhra Pradesh, India, *Tropical, hot, humid*	SWB-neutron (FAO-PM-ET_o)	Rainfed	1667 (3.0×2.0)	n/r	n/r	n/r	n/r
Fagbayide et al. (2019)	n/r	Akure, Ondo, Nigeria *Temp. trop humid*	DL, SWB-FDR (FAO-PM-ET_o)	Drip *FI*	4444 (1.5×1.5)	n/r	1	2.15	n/r
		Ilaro, Ogun, Nigeria *Temp. Trop humid*						1.07	
Lena et al. (2021)	n/r	Piracicaba, SP, BR *Subtrop humid hot*	WL (FAO-PM-ET_o)	Sprinkler, Drip *FI*	833 (4.0×3.0)	n/r	1 2 3 4	0.8 2.1 2.6 2.9	n/r

main one being the SWB; one used WL and another used EC. The orchards were irrigated with sprinkler and drip irrigation with most schedules aimed at satisfying crop water requirements. The plant densities ranged from 3125 to 7619 plants/ha. Most studies were performed in coffee orchards with <4 years. No information was available relative to f_c and only one study reported on plant height of around 2 m. For most cases, the lower K_c values were obtained in the studies developed in the younger orchards (Table 8), which relates to the lower tree development. The K_c values for full bearing orchards (Lena et al. 2011; Vale Sant'Ana et al. 2022) presented a small variation in the values of the $K_{c\ ini}$ and $K_{c\ end}$, ranging 0.70–0.83, while K_c mid ranged 0.70–1.06 (Table 8).

Jabuticaba (*Plinia peruviana* (Poir.) Govaerts) is a subtropical evergreen fruit tree endemic from Brazil, which is the main producer particularly in the southeast (Oliveira et al. 2019). It is considered a cauliflorous tree because its

Table 7 (continued)

Author	Cultivar (rootstock)	Location & *main climate*	Field method for $ET_{c\ act}$ (ET_o equation)	Irrigation method & *strategy*	Trees/ha (Spacing, m)	Training system	Age (years)	Height (m)	f_c or f_{IPAR}
Macadamia (*Macadamia integrifolia* Maiden & Betche)									
Ibraimo et al. (2014)	Beaumont (695) (Beaumont)	White River, Mpumalanga, S.Africa, *Subtropical*	SF, OPEC, micro-lys, SWB TDR (FAO-PM ET_o)	Drip *FI*	312 (8 × 4)	central leader	6–7	5	0.64
Taylor et al. (2021)	Beaumont (Beaumont)	Nelspruit, Mpumalanga, South Africa, *Subtropical*		Micro-spr *FI, DI, rainfed*	312 (8 × 4)	n/r	11–13 5–7 1–2	5.7 4.2 1.6	0.60–0.72 0.40–0.50 0.08–0.15
Mashabatu et al. (2023)	Beaumont (Beaumont)	White River Mpumalanga, S Africa, *Subtropical*		Drip *FI*	312 (8 × 4)	central leader	6–7 11	5 5.7	0.64 0.72

flowers sprout directly from the trunk and branches (Gomes et al. 2007). Under favourable conditions, it can bear fruit all year round. A single study on K_c was available in the literature (Bergamaschi and Prua 2018), which was developed in a rainfed mature orchard with a plant density of 494 plants/ha, with high ground cover ($f_c = 0.80$) and trees reaching a height of 3.5 m. Despite being rainfed, sufficient water was available for the crop to assure no stress. The soil water balance was used for measuring $ET_{c\ act}$. The K_c values ranged from 0.90 to 1.06 with the higher value occurring during the mid-season (Table 8).

Jatropha (*Jatropha curcas* L.) is a deciduous shrub or tree species that grows on poor or less fertile soils and marginal areas. Jatropha is a non-food plant (due to its toxic watery sap) that is mostly used for biodiesel production and for the pharmaceutical industry (Fagbayide et al. 2019). Indonesia is the world's top producer. Three studies on the estimation of crop coefficients were selected (Garg et al. 2014; Fagbayide et al. 2019; Lena et al. 2021). Several methods were used for the measurement of $ET_{c\ act}$, namely SWB, DL, and WL (Table 7). One of the orchards was surveyed until reaching full bearing (Lena et al. 2021). The orchards presented a very wide range of plant densities, from 833 to 4444 plants/ha. Trees can reach a height of 2.9 m after maturity (Lena et al. 2021). The K_c values for this orchard ranged from 0.30 to 1.10, with the higher value observed during the mid-season stage (Table 8).

Macadamia (*Macadamia integrifolia* Maiden & Betche) is an increasingly important crop in South Africa, which is the main world producer. Macadamia is a fast-growing, medium-sized evergreen tree with long green leaves native to Australia. All the selected studies were developed in South Africa in seven orchards. After five years of planting, Macadamia trees can bear nuts and reach full production after ten years. Thus, only two orchards were full bearing. The macadamia tree is trained in a single main trunk (central leader modified), but an untrained tree may be a better option (Taylor et al. 2021). The propagation method is by grafting or budding onto rootstocks; all the studied orchards used Beaumont rootstock. The most used plant density ranges between 200 and 360 plants/ha, and in the selected studies it was 312 plants/ha. A set of methods were used for $ET_{c\ act}$ measurements nanely EC, SWB, sap flow and microlysimeters. The orchards were drip or micro-sprinkler irrigated. The trees height reached 5.7 m in the fully bearing orchards, while the f_c ranged between 0.60 and 0.72. The Macadamia trees exhibit a strong stomatal control of transpiration responding to increases in atmospheric demand, resulting in low F_r values and crop coefficients (K_c) (Mashabatu et al. 2023). In other words, macadamia trees can maintain leaf water potential even in high atmospheric demand. The K_c values were only available for one of the studies, for a non-full bearing orchard, with similar $K_{c\ ini}$ and $K_{c\ end}$ values of 0.55 and a $K_{c\ mid}$ of 0.68 (Table 8). Results show that the K_{cb} values are highly linked with the f_c values and tree heights. Therefore, the $K_{cb\ ini}$ values ranged from 0.10–0.45, $K_{cb\ mid}$ values ranged from 0.26–0.45 while $K_{cb\ end}$ values ranged from 0.10–0.35.

The Table 9 shows the standard initial, mid- and end-season K_c and K_{cb} values for acerola, carambola, cashew, cacao,

Table 8 Field derived crop coefficients of selected acerola, carambola, cashew, cacao, coffee, jaboticaba, jatropha, macadamia orchards

Author	Cultivar (rootstock)	Training system	f_c or f_{IPAR}	Height (m)	Ground cover	Age	K_c /K_{cb} derived from field observations					
							$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
Acerola (*Malpighia emarginata* DC.)												
Konrad (2002)	Oliver	n/r	n/r	n/r	n/r	3	n/r	1.00	n/r	n/r	n/r	n/r
Santos et al. (2014)	n/r	n/r	n/r	n/r	n/r	2	n/r	0.88	n/r	n/r	n/r	n/r
Carambola (*Averrhoa carambola*)												
Kisekka et al. (2010)	Arkin	n/r	n/r	n/r	n/r	15	1.00	1.15	1.10	n/r	n/r	n/r
Cashew (*Anacardium occidentale* L.), Early maturity dwarf												
Miranda et al. (2013)	n/r	n/r	0.05–0.10 0.10–0.25 0.25–0.40 0.40–0.50 0.60–0.65	n/r	n/r	1 2 3 4 >5	0.50 0.55 0.55 0.60 0.65	0.50 0.55 0.55 0.60 0.65	0.50 0.55 0.55 0.60 0.65	n/r	n/r	n/r
Gondim et al. (2020)	BRS 266	n/r	n/r	0.72	n/r	1	0.29	0.60	0.87	n/r	n/r	n/r
Cacao (*Theobroma cacao* L.)												
López-López et al. (2013)	INIFAP F-7 hybrid	n/r	n/r	n/r	n/r	10	0.60	0.70	0.70	n/r	n/r	n/r
Waldburger et al. (2019)	CCN51 (Parazinho)	vase	n/r	3	n/r	4–7	1.04	1.04	1.04	n/r	n/r	n/r
Kaimuddin et al. (2020)	n/r	n/r	n/r	n/r	n/r	8	0.90	0.96	0.95	n/r	n/r	n/r
Coffee (*Coffea arabica* L.)												
Silva et al. (2009)	IAC-44	n/r	n/r	n/r		3–4	1.10	1.10	1.10	n/r	n/r	n/r
Lena et al. (2011)	Iapar 59 Irrig	n/r	n/r	n/r	n/r	5–6	0.83	1.06	0.82	n/r	n/r	n/r
	n/irrig						0.68	1.00	0.71	n/r	n/r	n/r
Pereira et al. (2011)	IAC 388–17 (Apoatã 2258)	n/	n/r	n/r	BS	2	0.25	0.25	0.25	n/r	n/r	n/r
						4	0.82	0.82	0.82	n/r	n/r	n/r
Castaño-Marín et al. (2021)	Castillo Paraguaicito	n/r	n/r	n/r	n/r	3–4	0.97	0.97	0.97	n/r	n/r	n/r
Vale Sant'Ana et al. (2022)	Catiguá MG-3	n/	n/r	2.09	n/r	1–2 3–4 5–6	0.27 0.52 0.70	0.27 0.52 0.70	0.27 0.52 0.70	n/r	n/r	n/r
Jaboticaba (*Plinia peruviana* (Poir.) Govaerts)												
Bergamaschi and Prua (2018)	n/r	n/r	0.80	3.5	n/r	10–12	0.90	1.06	1.00	–	–	–
Jatropha (*Jatropha curcas* L.)												
Garg et al. (2014)	n/r	n/r	n/r	n/r	n/r	n/r	0.20	0.93	0.10	n/r	n/r	n/r
Fagbayide et al. (2019)	n/r	n/r	n/r	2.15	BS	1	0.50	1.10	0.50	n/r	n/r	n/r
Lena et al. (2021)	n/r	n/r	n/r	0.8 2.1 2.6 2.9	BS	1 2 3 4	n/r 0.30 0.30 0.30	0.60 0.80 1.05 1.10	n/r 0.30 0.30 0.30	n/r	n/r	n/r

Table 8 (continued)

Author	Cultivar (rootstock)	Training system	f_c or f_{IPAR}	Height (m)	Ground cover	Age	K_c /K_{cb} derived from field observations					
							$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
Macadamia (*Macadamia integrifólia* Maiden & Betche)												
Ibraimo et al. (2014)	Beaumont 695	Central leader	0.64	5	n/r	6–7	0.56	0.68	0.55	0.30	0.45	0.35
Taylor et al. (2021)	Beaumont 695	n/r	0.60–0.72	5.7	AGC	11–13	n/r	n/r	n/r	0.20	0.26	0.18
			0.40–0.50	4.2		5–7	n/r	n/r	n/r	0.12	0.17	0.16
			0.08–0.15	1.6		1–2	n/r	n/r	n/r	0.10	0.10	0.10
Mashabatu et al. (2023)	Beaumont 695	n/r	0.64	5	n/r	6–7	n/r	n/r	n/r	0.30	0.45	0.35
			0.72	5.7		11	n/r	n/r	n/r	0.30	0.30	0.30

coffee, jaboticaba, jatropha and macadamia, which are grouped according to the degree of ground cover, plant density and training system as previously reported for Table 3. Table 9 also includes the K_c/K_{cb} values derived from the selected studies, as well as the previous tabulated standard K_c and K_{cb} values, only available for cacao and coffee (Allen et al. 1998, Jensen and Allen 2016; Rallo et al. 2021), which were the bases for the proposed standard values. However, due to the lack of observed or previously tabulated K_c and K_{cb} values for the other crops, most of the proposed standard K_c and K_{cb} values were calculated using the A&P method (Pereira et al. 2020a, b). Due to scarce information in the selected papers, the values of plant densities and degree of ground cover included in Table 9 result from values commonly found for commercial orchards, and therefore should be viewed as indicative.

As mentioned previously, the suggested standard K_{cb} values increase when f_c increases due to the close relationship between K_{cb} and f_c. Since K_c also varies due to the soil evaporation component (K_e), which is determined primarily by the frequency and depth of rainfall or irrigation events, as well as the energy available for soil water evaporation, this fraction is determined by the radiation intercepted by the canopy. i.e. through the f_c values as for the dual K_c proposed in FAO56 (Allen et al. 1998).

Palm, fiber and rubber plantations

The main characteristics of the plantations referred to in this section are presented below and summarized in Table 10, while the observed K_c/K_{cb} values are presented in Table 11. Main plantations herein considered are palm plantations. Palms are perennial monocotyledonous plants characterized by a woody stem. Palm trees thrive in humid and hot climates but are found in various habitats.

Açai Palm (*Euterpe oleracea* Mart.) is a palm tree typically found in the floodplains of the Amazon biome in Northern Brazil (Sousa et al. 2021). Its fruit is a worldwide increasingly popular superfood in the twenty-first century. Açai fruits and hearts of palm are eaten as vegetables. Few studies are available and only one, carried out in Brazil (Sousa et al. 2021), was selected. Supplemental irrigation is important during the fruiting phase, from March to October, which corresponds to the mid-season stage (Sousa et al. 2021). The study was conducted in a mature orchard, with an average plant height of 10 m and a plant density of 417 plants/ha, irrigated with micro-sprinklers (Table 10). The $ET_{c\ act}$ was measured using a BREB equipment, while soil evaporation was measured using microlysimeters, which permitted to compute K_e and K_{cb}. The K_c and Kcb values vary little along the season, thus with

Table 9 Initial, mid- and end-season standard single and basal crop coefficients for acerola, carambola, cashew, cacao, coffee, jaboticaba, jatropha, macadamia orchards as related with the fraction of ground cover and height

Degree of ground cover/training	f_c	h		M_L	F_r	Field reported values		Previously tabulated		Proposed values	
						K_{cb}	K_c	K_{cb}	K_c	K_{cb}	K_c
Acerola (*Malpighia emarginata* DC.*)*											
Young (<5 years)	<0.50	<2.0	Ini	1.1	1.00			–	–	**0.35**	**0.50**
			Mid	1.2	1.00		0.88–1.00	–	–	**0.45**	**0.60**
			End	1.2	1.00			–	–	**0.40**	**0.55**
Medium–High (278–625 plants/ha)	0.50–0.70	2.0–4.0	Ini	1.4	0.60			–	–	**0.60**	**0.70**
			Mid	1.5	0.65			–	–	**0.65**	**0.85**
			End	1.5	0.65			–	–	**0.60**	**0.70**
			Mid	2.0	1.00	–	–	–	–	**0.85**	**0.95**
			End	2.0	0.65	–	–	–	–	**0.50**	**0.65**
Carambola (*Averrhoa carambola* L.)											
Young (<4 years)	<0.40	<2.00	Ini	1.80	1.00	–	–	–	–	**0.55**	**0.75**
			Mid	1.90	1.00	–	–	–	–	**0.90**	**1.00**
			End	1.90	1.00	–	–	–	–	**0.70**	**0.90**
Common density (150–300 plants/ha)	0.40–0.60	2.0–4.00	Ini	1.80	0.90	–	1.00	–	–	**0.85**	**1.00**
			Mid	2.00	1.00	–	1.15			**1.05**	**1.15**
			End	2.00	0.98	–	1.10			**1.00**	**1.10**
Cashew (*Anacardium occidentale* L.), **early maturity dwarf**											
Young (<2 years)	<0.50	<3.0	Ini	1.0	1.00	–	0.29–0.55	–	–	**0.30**	**0.50**
			Mid	1.3	1.00	–	0.50–0.60	–	–	**0.50**	**0.60**
			End	1.3	1.00	–	0.50–0.87	–	–	**0.40**	**0.55**
Common density (178–313 plants/ha)	0.50–0.65	3.0–5.0	Ini	1.3	0.70	–	0.55–0.65	–	–	**0.55**	**0.65**
			Mid	1.5	0.60	–	0.55–0.65	–	–	**0.60**	**0.65**
			End	1.5	0.60	–	0.55–0.65	–	–	**0.55**	**0.65**
Cacao (*Theobroma cacao* L.)											
Young (<4 years) shading	<0.50	<2.0	Ini	1.3	1.00	–	–	–	–	**0.45**	**0.60**
			Mid	1.8	1.00	–	–	–	–	**0.65**	**0.80**
			End	1.6	1.00	–	–	–	–	**0.60**	**0.75**
Medium, shading (<1000 plants/ha)	0.50–0.70	2.0–2.5	Ini	1.5	0.80	–	–	–	–	**0.80**	**0.90**
			Mid	2.0	0.83	–	–	–	–	**0.85**	**0.95**
			End	2.0	0.83	–	–	–	–	**0.85**	**0.95**
High, shading (1000–1900 plants/ha)	>0.70	>2.0	Ini	1.8	0.80	–	0.60–1.04	0.90	1.00	**0.90**	**1.00**
			Mid	2.0	0.83	–	0.70–1.04	1.00	1.05	**0.95**	**1.05**
			End	1.8	0.83	–	0.70–1.04	1.00	1.05	**0.95**	**1.05**
Coffee (*Coffea arabica* L.)											
Young (<4 years)	<0.20	<2.5	Ini	1.6	1.00	–	0.25–1.10	–	–	**0.30**	**0.40**
			Mid	1.6	1.00	–	0.25–1.10	–	–	**0.35**	**0.55**
			End	1.6	1.00	–	0.25–1.10	–	–	**0.35**	**0.50**
Low-Medium (3000–6000 plants/ha)	0.20–0.50	2.5–3.5	Ini	1.8	0.80	–	0.83	–	–	**0.60**	**0.65**
			Mid	1.8	0.85	–	1.06	–	–	**0.70**	**0.80**
			End	1.8	0.85	–	0.82	–	–	**0.70**	**0.80**
High (including hedgerow) (>6000 plants/ha)	>0.50	>2.5	Ini	1.8	0.80	–	0.70	0.80	0.90	**0.85**	**0.90**
			Mid	1.8	0.85	–	0.70	0.90	0.95	**0.90**	**1.00**
			End	1.8	0.85	–	0.70	0.90	0.95	**0.90**	**1.00**
Jaboticaba (*Plinia peruviana* (Poir.) Govaerts)											
Young (<5 years)	<0.50	<2.0	Ini	1.0	1.00	–	–	–	–	**0.35**	**0.50**
			Mid	1.1	1.00	–	–	–	–	**0.45**	**0.65**
			End	1.1	1.00	–	–	–	–	**0.40**	**0.55**

Table 9 (continued)

Degree of ground cover/training	f_c	h		M_L	F_r	Field reported values		Previously tabulated		Proposed values	
						K_{cb}	K_c	K_{cb}	K_c	K_{cb}	K_c
Common density (250–500 plants/ha)	>0.50	>2.5	Ini	1.3	0.60	–	0.90	–	–	**0.55**	**0.70**
			Mid	1.4	0.80	–	1.06	–	–	**0.80**	**0.95**
			End	1.4	0.70	–	1.00	–	–	**0.65**	**0.80**
Jatropha (*Jatropha curcas* L.)											
Young (<2 years), vase	<0.15	<1.0	Ini	1.6	1.00	–	0.50	–	–	**0.25**	**0.45**
			Mid	1.7	1.00	–	0.60–1.10	–	–	**0.25**	**0.45**
			End	1.7	1.00	–	0.50	–	–	**0.25**	**0.45**
Low-Medium, vase (1100–1500 plants/ha)	0.15–0.35	1.0–2.0	Ini	1.7	0.90	–	–	–	–	**0.35**	**0.50**
			Mid	1.8	0.90	–	–	–	–	**0.55**	**0.70**
			End	1.8	0.90	–	–	–	–	**0.40**	**0.55**
High, vase (>1500 plants/ha)	>0.35	>2.0	Ini	1.7	0.90	–	0.30	–	–	**0.55**	**0.65**
			Mid	1.8	0.90	–	0.80–1.10	–	–	**0.80**	**0.90**
			End	1.8	0.90	–	0.30	–	–	**0.70**	**0.75**
Macadamia (*Macadamia integrifolia* Maiden & Betche)											
Young (<10 years)	<0.50	<2.0	Ini	1.1	1.00	0.10–0.30	0.56	–	–	**0.35**	**0.55**
			Mid	1.2	1.00	0.10–0.45	0.68	–	–	**0.50**	**0.55**
			End	1.2	1.00	0.10–0.35	0.55	–	–	**0.40**	**0.50**
Medium–High (plants/ha)	>0.50	2.0–4.5	Ini	1.5	0.55	0.20–0.30	–	–	–	**0.55**	**0.75**
			Mid	1.7	0.55	0.26–0.30	–	–	–	**0.60**	**0.75**
			End	1.7	0.50	0.18–0.30	–	–	–	**0.55**	**0.70**

initial and end-season values close to the mid-season ones, which are high (Table 11).

Coconut (*Cocus nucifera* L.) is an evergreen single-stemmed palm that mainly grows in the tropics and subtropics between 20° North and South latitudes (Miranda et al. 2007). Top producers include Indonesia, the Philippines, India and Brazil. Nowadays, dwarf or semi-dwarf coconut palms, with a height lowered to 7 m, are preferred because they can produce much early than traditional cultivars (Teixeira et al. 2019). Research studies on crop water requirements and K_c are, however, scarce. The two selected studies were performed in dwarf coconut orchards, located in the northeast of Brazil, irrigated with micro-sprinklers and having a plant density of 115 to 178 plants/ha (Table 10). A SWB approach (Miranda et al. 2007) and a remote sensing VI method (Teixeira et al. 2019) were used to estimate $ET_{c\ act}$. The f_c ranged from 0.30 to 0.85 in accordance with the age of the orchard (Table 10). The K_c values in Table 11 showed a tight relation with f_c values. $K_{c\ mid}$ values ranged from 0.75 to 1.02.

Date Palm (*Phoenix dactylifera* L.) is a palm tree grown in many tropical regions worldwide for its sweet edible fruits. The date palm may have originated in Mesopotamia. The fruit has been the staple food and a major source of wealth in the oasis of North Africa and the Middle East. The main worlds' producer is Egypt, followed by Saudi Arabia. Eleven studies were selected, most of them performed in Saudi Arabia (Kassem 2007; Alamoud et al. 2012; Ismail et al. 2014; Al-Qurashi et al. 2016; Alharbi et al. 2016), and one in Egypt (Sadik et al. 2018), Emirates (Al-Muaini et al. 2019), Israel (Sperling et al. 2014), Jordan (Mazahrih et al. 2012), Kuwait (Bhat et al. 2012), and USA (Montazar et al. 2020). Most studies used the SWB method for estimating $ET_{c\ act}$, while two others used lysimeters (WL or DL), one used EC and SR (Table 10) and another used SF measurements for estimating crop transpiration (Al-Muaini et al. 2019). All plantations used localized irrigation (drip, bubbler, or microjet), but one combined localized and surface irrigation (Montazar et al. 2020). The plant density ranged from 100 to 204 plants/ha is commonly used, and the mean tree height of the full bearing plantations ranged from 2.2 m (Mazahrih et al. 2012) to 11.5 m (Montazar et al. 2020). Information on f_c from a few studies ranged between 0.20 and 0.81. The K_c values (Table 11) show a wide range of variation in both young and mature plantations due to differences in cultivars and management, generally showing $K_{c\ ini}$ and $K_{c\ end}$ not far from $K_{c\ mid}$ as common with evergreen trees.

Guayule (*Parthenium argentatum* A. Gray) is a perennial shrub, with ratoon-cropping potential for multiples harvests, usually every 2-years and is being commercially exploited for up to 10 years. It is native to the deserts of the southern

Table 10 Characteristics of selected palm, fiber and rubber plantations

Author	Cultivar (rootstock)	Location & *main climate*	$ET_{c\ act}$ method (ET_o eq.)	Irrig. Method & strategy	Trees/ha (Spacing, m)	Training system	Age (years)	Height (m)	f_c or f_{IPAR}
Açaí palm (*Euterpe oleracea* Mart.)									
Sousa et al. (2021)	Chumbinho	Capitão Poço, Pará, Brazil *Trop. Humid and warm*	BREB + ML (FAO-PM ET_o)	Mic-spr FI	417 (6 × 4)	3 plants/ clump	8 9	10	n/r
Coconut (*Cocos nucifera* L.)									
Miranda et al. (2007)	Jiqui Dwarf	Paraipaba, Ceará, Brazil *Trop. Semi-arid, Hot*	SWB tensiom (FAO-PM ET_o)	Mic-spr FI	178 (7.5 × 7.5)	n/r	2 3 4	n/r	0.30 0.60 0.85
Teixeira et al. (2019)	Jiqui Dwarf	Camocim, Ceará, Brazil *Trop. Semi-arid, Hot*	RS-NDVI, SAFER (FAO-PM ET_o)	Mic-spr FI	115 (10 × 10)	n/r	3 to 5	5	0.45
Date palm (*Phoenix dactylifera* L.)									
Kassem (2007)	Sukariah	Al-Qassim, Saudi Arabia *Desert. Hot and dry*	SWB- tensiom (FAO-PM ET_o)	Drip FI	156 (8 × 8)	n/r	15	2.5	n/r
Alamoud et al. (2012)	n/r	Seven regions of S. Arabia *Desert. Hot and dry*	SWB-tensiom (ASCE-PM Etr)	Drip FI	100 (10 × 10)	n/r	Mature	n/r	n/r
Bhat et al. (2012)	Siwi, Nabusaif & Khalas	Kuwait *Desert, hot and dry*	DL (FAO-PM ET_o)	Drip FI	n/r	n/r	1	n/r	n/r
Mazahrih et al. (2012)	Medjool	Balqa' region, Jordan *Semiarid. Dry and hot*	SWB- neutron (FAO-PM ET_o)	Drip FI and DI	156 (8 × 8)	n/r	12	2.2	0.47
Ismail et al. (2014)	Nabbut-Saif	Jedda region, Saudi Arabia *Desert. Hot and dry*	SWB- gravim (FAO-PM ET_o)	Drip FI and DI	n/r	n/r	Mature	n/r	n/r
Sperling et al. (2014)	Medjool	Yotvata, Israel *Arid, hot and dry*	WL (FAO-PMET$_o$)	Drip FI	123 (9 × 9)	n/r	12	10	n/r
Al-Qurashi et al. (2016)	Barhee	Jeddah, Saudi Arabia *Desert. Hot and dry*	SWB-gravim (FAO-PM ET_o)	Drip FI	100 (10 × 10)	n/r	5 6	4.30	n/r
Alharbi et al. (2016)	Soukry	Buraidah, Qassim, S.Arabia *Desert. Hot and dry*	SWB-FDR (FAO-PM ET_o)	n/r FI	n/r	n/r	8	n/r	n/r
Sadik et al. (2018)	Siwy	Giza Governorate, Egypt *Desert. Hot and dry*	SWB-gravim (FAO-PM ET_o)	Mic-jet/Drip FI	204 (7 × 7)	n/r	8 9	n/r	0.70

Table 10 (continued)

Author	Cultivar (rootstock)	Location & *main climate*	$ET_{c\ act}$ method (ET_o eq.)	Irrig. Method & strategy	Trees/ha (Spacing, m)	Training system	Age (years)	Height (m)	$f_{c\ or}\ f_{IPAR}$
Al-Muaini et al. (2019)	Lulu	Dubai, United Arab Emirates *Desert. Hot and dry*	SF (FAO-PM ET_o)	Bubbler FI	156 (8 × 8)	n/r	16	3.58 2.62	0.26 0.20
Montazar et al. (2020)	Medjool	Coachella Valley, CA, USA	EC and SR (FAO-PM ET_o)	Drip + surf	125 (8.8 × 9.1)	n/r	8	n/r	n/r
	Deglet Noor			Drip + surf			17	11.5	0.81
	Deglet Noor			Drip + surf	120 (9.1 × 9.1)		20	11.5	0.81
	Deglet Noor			Surface	120 (9.1 × 9.1)		22	11.5	0.81
	Deglet Noor	Imperial Valley, CA, USA		Mic-spr/surf	149 (8.2 × 8.2)		17	7.3	0.55
	Medjool			Surface	120 (9.1 × 9.1)		15	n/r	n/r
Guayule (*Parthenium argentatum* A. Gray)									
Elshikha et al. (2021)	AZ2 (n.a.)	Maricopa and Eloy, Arizona State, USA Semi-arid desert	SWB-neutron (FAO-PM ET_o)	SDI/ furrow FI	44,000 (n/r) 78,000 (n/r)	n/a	1–2	0.95 1.05	0.70–1.00
Oil palm (*Elaeis guineensis* Jacq.)									
Kallarackal et al. (2004)	Tenera and Palode	Andhra Pradesh, Karnataka and Maharashtra, India *Tropical hot and humid*	T_c from PM-eq (Pan evap.)	n/r FI	148 (9 × 9)	n/r	Mature	n/r	n/r
Henson et al. (2005, 2007)	n/r	Sintok, Kedah, Malaysia *Tropical hot and humid*	EC, SWB-FDR-TDR (Penman ET_o)	Rainfed	148 (n/r)	n/r n/r	4–6	n/r	n/r
Santos (2019)	Compact x Ghana	Piracicaba, São Paulo, Brazil *Subtropical hot and humid*	WL & dual-Kc (FAO-PM ET_o)	Drip FI	143 (9 × 9 triangular)	n/r	2 3 4–9	2.2 2.3 n/r	0.09 0.14 n/r
Peach palm (*Bactris gasipaes* Kunth)									
Ramos (1998)	n/r	Piracicaba, São Paulo, Brazil	WTL, SWB (grass-lys. ET_o)	Drip	5000 (2 × 1)	n/r	3	1.5	n/r
Bassoi et al. (2003)	n/r	Juazeiro, Bahia, Brazil Tropical hot and dry	SWB (class A pan)	Mic-spr	5000 (2 × 1)	n/r	1–3	1.2–1.6	n/r
Lopes et al. (2004)	n/r	Ilha Solteira, São Paulo, Brazil	DL & SWB (class A pan)	Sprinkler	5000 (2 × 1)	n/r	1–3	1.8	0.30

Table 10 (continued)

Author	Cultivar (rootstock)	Location & *main climate*	$ET_{c\ act}$ method (ET_o eq.)	Irrig. Method & strategy	Trees/ha (Spacing, m)	Training system	Age (years)	Height (m)	$f_{c\ or}\ f_{IPAR}$
Ramie (*Boehmeria nivea* (L.) Gaudich.)									
Mitra et al. (2018)	Kanai (R-67-34) (n.a.)	Barrackpore, Bengel, India Moonson tropical	SWB-grav (FAO-PM ET_o)	Furrow FI	n/r	n/a	1–3	n/r	n/r
Rubber tree (*Hevea brasiliensis* L.)									
Vijayakumar et al. (1998)	RRII 105 (clone)	Dapchari, India humid tropical	K_c-biomass test (Penman ET_o)	Basin, drip FI	400 (4.9×4.9)	n/r	4–7	n/r	<0.9
Ling et al. (2023)	n/r	Xishuang-banna, Yunnan, China	BREB, SWB-cap (HS-ET_o)	n/r FI	300 ± 50 (n/r)	n/r	15	11.6 ± 2	n/r

United States and northern Mexico, known as a source of natural rubber (Table 10). It is drought tolerant and grows better at air temperatures above 18 °C. A single study was selected focusing on guayule water requirements (Elshikha et al. 2021), conducted in Arizona in two young plantations having plant densities of 44,000 and 78,000 plants/ha (Table 10). Plants height ranged from 0.95 to 1.05 m, and a full ground cover was reached ($f_c = 1$) in both plantations. The plantations were irrigated with sub-surface drip and furrow irrigation. SWB was used for the estimation of $ET_{c\ act}$. Table 11 presents the K_c and K_{cb} values adjusted to standard climate conditions provided by Elshikha et al. (2021) for both plantations, which show $K_{c\ mid}$ values, of around 1.20, about doubling $K_{c\ ini}$ and $K_{c\ end}$ (Table 11). Because guayule is typically harvested commercially every two years the reported standard K_c/K_cb values refer to two groups (Table 12). The first group refers to both the young plantations and the seasons after each harvest (third, fifth, seventh, ninth year after sowing/planting), i.e. the time when the crop is not yet fully developed. The other group refers to the years when the plant is fully developed and harvested. In this case, the plant reaches its potential and therefore the K_c/K_{cb} levels are higher since the beginning of the season.

Oil Palm (*Elaeis guineensis* Jacq.) is a perennial crop native to West Africa, grown in tropical environments, and is a very important source of vegetable oil. Indonesia, followed by Malaysia, is the largest palm oil-producing country. Few studies are available in the literature relative to the water use of oil palm. The selected articles originate in Brazil (Santos 2019), India (Kallarackal et al. 2004), and Malaysia (Henson et al. 2005, 2007). Most studies were developed in mature plantations, with a density of 143–148 plants/ha, and were irrigated.

$ET_{c\ act}$ was measured with WL or the combination of EC and SWB. In one case, crop transpiration was determined with the PM combination equation, thus allowing to derive K_{cb} values (Kallarackal et al. 2004). Few information was available relative to plants height, which was 2.2–2.3 m for a non-mature orchard (Santos 2019). The K_{cb} values for young plantations vary in a wide range related with the increase in f_c (Santos 2019). The $K_{cb\ mid}$ values for the mature orchards ranged from 0.85 to 1.15.

Peach palm (*Bactris gasipaes* Kunth), also called “pupunha,” is native to the tropical forests of Central and South America. The cultivation serves a dual purpose, the fruits and the edible heart-of-palm or “palmito”. The world’s top producers are Brazil, Colombia, and Peru. Despite studies reporting data on water use are scarce, three studies were selected, all conducted in Brazil (Ramos 1998; Bassoi et al. 2003; Lopes et al. 2004). In two of them, the plantations were surveyed from planting to maturity (Bassoi et al. 2003; Lopes et al. 2004), while the other was conducted on a mature plantation (Ramos 1998). The plant density, used in commercial areas and in the selected studies, is 5000 plants/ha, while h ranged between 1.5 and 2 m. The information on f_c was only available in one study, with $f_c = 0.30$ (Lopes et al. 2004). All studies used SWB to measure $ET_{c\ act}$, but two of them also used lysimeters (Ramos 1998; Lopes et al. 2004). The plantations were irrigated with localized or sprinkler irrigation. Table 11 includes the K_c values showing that $K_{c\ ini}$ and $K_{c\ end}$ are close or equal to $K_{c\ mid}$ in mature plantations, with $K_{c\ mid} \geq 1.0$.

Ramie (*Boehmeria nivea* (L.) Gaudich) is a perennial herbaceous plant that produces fibre. The largest producer is China, followed by Brazil, the Philippines, and India. Only one study on water use and crop coefficients was available in literature (Mitra et al. 2018) but information provided is very restrict. The study was developed along three years on a furrow irrigated plantation located in India. $ET_{c\ act}$ was

Table 11 Field derived crop coefficients of palm, fiber and rubber plantations

Author	Cultivar (rootstock)	Training system	f_c or f_{IPAR}	Height (m)	ground cover	Age	K_c /K_{cb} derived from field observations					
							$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
Açaí palm (*Euterpe oleracea* Mart.)												
Sousa et al. (2021)	Chumbinho	3 stumps p/plant	n/r	10	n/r	8 9	0.89 0.96	1.15 1.05	1.10 0.90	0.72 0.85	0.90 0.90	0.82 0.77
Coconut (*Cocos nucifera* L.)												
Miranda et al. (2007)	Jiqui Dwarf	n.a	0.30 0.60 0.85	n/r	AGC	2 3 4	n/r	0.80 0.95 1.02	n/r	n/r	n/r	n/r
Teixeira et al. (2019)	Jiqui Dwarf	n.a	0.45	5	AGC	3 4 5	n/r	0.82 0.75 0.82	0.64 0.55 0.50	n/r	n/r	n/r
Date palm (*Phoenix dactylifera* L.)												
Kassem (2007)	Sukariah	n/r	n/r	2.5	n/r	15	0.57	0.70	0.61	n/r	n/r	n/r
Alamoud et al. (2012)	n/r	n/r	n/r	n/r	n/r	Mature	0.80	0.99	0.88	n/r	n/r	n/r
Bhat et al. (2012)	Siwi	n/r	n/r	n/r	n/r	2	0.68	1.04	0.88	n/r	n/r	n/r
	Nabusaif						0.43	0.92	0.75			
	Khalas						0.68	1.08	0.75			
Mazahrih et al. (2012)	Medjool	n/r	0.47	2.2	n/r	12	0.76	1.15	0.50	n/r	n/r	n/r
Ismail et al. (2014)	Nabbut-Saif	n/r	n/r	n/r	n/r	Mature	0.56	0.77	0.72	n/r	n/r	n/r
Sperling et al. (2014)	Medjool	n/r	n/r	10	n/r	12	0.55	0.65	0.45	n/r	n/r	n/r
Al-Qurashi et al. (2016)	Barhee	n/r	n/	4.30	BS	5–6	0.85	1.26	0.65	n/r	n/r	n/r
Alharbi et al. (2016)	Soukry	n/r	n/r	n/r	n/r	8	0.85	1.00	0.85	n/r	n/r	n/r
Sadik et al. (2018)	Siwy Bubbler Microjet Drip	n/r	0.70	n/r	BS	8–9	0.62 0.55 0.52	0.75 0.62 0.58	0.66 0.57 0.49	n/r	n/r	n/r
	Bubbler Microjet Drip				Pl mulch	8–9	0.58 0.60 0.43	0.55 0.59 0.45	0.50 0.52 0.37			
Al-Muaini et al. (2019)	Lulu	n/r	0.26	3.58	BS	16	n/r	n/r	n/r	n/r	0.29	n/r
Montazar et al. (2020)	Medjool	n/r	n/r	n/r	n/r	8	0.64	0.80	0.63	n/r	n/r	n/r
	Deglet Noor		0.81	11.5		17	0.68	0.90	0.64			
	Deglet Noor		0.81	11.5		20	0.67	0.90	0.63			
	Deglet Noor		0.81	11.5		22	0.65	0.88	0.64			
	Deglet Noor		0.55	7.3		17	0.64	0.75	0.62			
	Medjool		n/r	n/r		15	0.64	0.80	0.65			

Table 11 (continued)

Author	Cultivar (rootstock)	Training system	f_c or f_{IPAR}	Height (m)	ground cover	Age		K_c /K_{cb} derived from field observations					
								$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
Guayule (*Parthenium argentatum* A. Gray)													
Elshikha et al. (2021)	AZ-2	n/r	1.00	0.95	BS	SDI	1	0.65	1.19	0.61	0.20	1.08	0.36
	(n.a.)						2	0.55	1.24	0.49	0.50	1.22	0.49
				1.05		Surf	1	0.75	1.20	0.53	0.20	1.08	0.43
							2	0.60	1.17	0.48	0.55	1.16	0.48
Oil palm (*Elaeis guineensis* Jacq)													
Kallarackal et al. (2004)	Tenera + Palode	n.a	n/r	n/r	n/r	Mature		n/r	n/r	n/r	0.77	0.85	0.77
Henson et al. (2005, 2007)	n/r	n.a	n/r	n/r	AGC	4		n/r	0.80	n/r	n/r	n/r	n/r
						5		n/r	0.95	n/r			
						6		0.60	0.90	0.70			
Santos (2019)	Compact x Ghana	n.a	0.09	2.2	AGC	2		n/r	n/r	n/r	0.20	0.60	0.80
			0.14	2.3		3					0.80	1.00	1.10
			n/r	n/r		4–9					1.15	1.15	1.15
Peach palm (*Bactris gasipaes* Kunth)													
Ramos (1998)	n/r	n/r			n/r	3		0.70	1.05	0.80	n/r	n/r	n/r
Bassoi et al. (2003)	n/r	n/r		1.2–1.6	n/r	1–3		0.80	1.05	0.55	n/r	n/r	n/r
Lopes et al. (2004)	n/r	n/r		1.6	n/r	1		1.00	1.00	1.00	n/r	n/r	n/r
		n/r	0.30	1.8	n/r	3		1.30	1.30	1.30	n/r	n/r	n/r
Ramie (*Boehmeria nivea* (L.) Gaudich.)													
Mitra et al. (2018)	Kanai (R-67-34)	n/r	n/r	n/r	n/r	1–3 (5 cut/y)		n/r	0.82	n/r	n/r	n/r	n/r
Rubber tree (*Hevea brasiliensis* L.)													
Vijayakumar et al. (1998)	RRII 105	n/r	<0.90	n/r	n/r	4–7		n/r	1.25	n/r	n/r	n/r	n/r
Ling et al. (2023)	n/r	n/r	n/r	11.5	n/r	15		0.89	1.10	0.91	n/r	n/r	n/r

Table 12 Initial, mid- and end-season standard single and basal crop coefficients for palm, fiber and rubber plantations as related to the fraction of ground cover and height

Degree of ground cover, training	f_c	h		M_L	F_r	Field observed		formerly tabulated		Proposed values	
						K_{cb}	K_c	K_{cb}	K_c	K_{cb}	K_c
Coconut (*Cocos nucifera*) and **açaí palm** (*Euterpe oleracea*)											
Young coconut: traditional < 15 years, dwarf < 3 years; Young açaí palm < 3 years	<0.30	<2.5	Ini	1.3	1.00	–	–	0.25–0.40	0.35–0.50	**0.30**	**0.45**
			Mid	1.4	1.00	–	0.75–1.02	0.25–0.45	0.35–0.55	**0.35**	**0.55**
			End	1.4	1.00	–	0.50–0.64	0.25–0.45	0.35–0.55	**0.35**	**0.55**
Medium (100–150 plants/ha)	0.30–0.50	2.5–5.0	Ini	1.6	0.80	–	–	0.70	0.80	**0.60**	**0.75**
			Mid	1.6	0.80	–	–	0.70	0.80	**0.65**	**0.85**
			End	1.6	0.80	–	–	0.70	0.80	**0.65**	**0.85**
High (>150 plants/ha)	>0.50	>5.0	Ini	1.8	0.80	0.72–0.85	0.89–0.96	0.80–0.85	0.90–0.95	**0.90**	**0.95**
			Mid	1.9	0.80	0.80–0.90	1.05–1.15	0.85–0.90	0.95–1.00	**0.90**	**1.00**
			End	1.9	0.80	0.60–0.70	0.90–1.10	0.85–0.90	0.95–1.00	**0.90**	**1.00**
Date palm (*Phoenix dactylifera* L.)											
Young (<10 years)	<0.20	<4.0	Ini	1.4	1.00	–	0.43–0.85	0.25	0.35	**0.25**	**0.45**
			Mid	1.5	1.00	–	0.45–1.08	0.25	0.35	**0.35**	**0.45**
			End	1.5	1.00	–	0.37–0.88	0.25	0.35	**0.35**	**0.45**
Low to medium (100–130 plants/ha)	0.20–0.50	4.0–10.0	Ini	1.7	0.75	–	0.76	0.40–0.70	0.50–0.80	**0.50**	**0.70**
			Mid	1.8	0.75	0.29	1.15	0.45–0.70	0.55–0.80	**0.60**	**0.70**
			End	1.8	0.75	–	0.50	0.45–0.70	0.55–0.80	**0.60**	**0.70**
High (130–200 plants/ha)	0.50–0.70	5.0–12.0	Ini	1.7	0.75	–		0.70–0.80	0.80–0.90	**0.80**	**0.85**
			Mid	1.8	0.75	–		0.70–0.85	0.80–0.95	**0.85**	**0.85**
			End	1.8	0.75	–		0.70–0.85	0.80–0.95	**0.85**	**0.85**
Very high (>200 plants/ha)	>0.70	>10.0	Ini	1.7	0.75	–	0.64–0.68	–	–	**0.85**	**0.95**
			Mid	1.8	0.75	–	0.75–0.90	–	–	**0.95**	**0.95**
			End	1.8	0.75	–	0.62–0.65	–	–	**0.95**	**0.95**
Guayule (*Parthenium argentatum* A. Gray)											
First year after sowing/planting (young 1 year) or first year after harvest	<0.35	<0.80	Ini	1.1	1.00	0.20	0.65–0.75	–	–	**0.15**	**0.35**
			Mid	2.0	1.00	1.08	1.19-1.20	–	–	**0.95**	**1.05**
			End	2.0	0.55	0.36-0.43	0.53-0.61	–	–	**0.50**	**0.60**
Second year after sowing or second year after the harvest, Common density (20,000–55,000 plants/ha)	0.35–0.50	0.80–1.00	Ini	1.1	1.00	0.50-0.55	0.55-0.60	–	–	**0.60**	**0.70**
			Mid	2.0	1.00	1.16-1.22	1.17-1.24	–	–	**1.05**	**1.10**
			End	2.0	0.55	0.48-0.49	0.48-0.49	–	–	**0.55**	**0.65**
Oil palm (*Elaeis guineensis* Jacq.)											
Young (<3 years)	<0.30	<2.5	Ini	1.3	1.00	0.20–0.80	–	0.25–0.40	0.35–0.50	**0.30**	**0.45**
			Mid	1.3	1.00	0.60–1.00	–	0.25–0.45	0.35–0.55	**0.35**	**0.55**
			End	1.3	1.00	0.10–0.80	–	0.25–0.45	0.35–0.55	**0.35**	**0.55**

Table 12 (continued)

Degree of ground cover, training	f_c	h		M_L	F_r	Field observed		formerly tabulated		Proposed values	
						K_{cb}	K_c	K_{cb}	K_c	K_{cb}	K_c
Medium (100–150 plants/ha)	0.30–0.50	2.5–5.0	Ini	1.5	0.95	–	–	0.70	0.80	**0.60**	**0.75**
			Mid	1.5	0.95	–	–	0.70	0.80	**0.70**	**0.85**
			End	1.5	0.95	–	–	0.70	0.80	**0.70**	**0.85**
High (>150 plants/ha)	>0.50	>5.0	Ini	1.5	0.95	0.77–1.15	–	0.80–0.85	0.90–0.95	**0.85**	**0.95**
			Mid	1.5	0.95	0.85–1.15	–	0.85–0.90	0.95–1.00	**0.90**	**1.00**
			End	1.5	0.95	0.75–1.15	–	0.85–0.90	0.95–1.00	**0.90**	**1.00**
Peach palm (*Bactris gasipaes* Kunth)											
Young (<2.5 years)	<0.30	<2.0	Ini	1.2	1.00	–	1.00	–	–	**0.25**	**0.60**
			Mid	1.7	1.00	–	1.00	–	–	**0.50**	**0.80**
			End	1.5	1.00	–	1.00	–	–	**0.40**	**0.70**
Common density (3000–5000 plants/ha)	>0.30	>2.0	Ini	1.3	0.85	–	0.70–1.30	–	–	**0.55**	**0.80**
			Mid	1.8	0.85	–	1.05–1.30	–	–	**0.75**	**0.95**
			End	1.7	0.85	–	0.55–1.30	–	–	**0.70**	**0.90**
Ramie (*Boehmeria nivea* (L.) Gaudich.)											
Young (<2 years)	<0.80	0.70–2.0	Ini	1.0	0.85	–	–	–	–	**0.15**	**0.25**
			Mid	1.6	0.85	–	0.82	–	–	**0.55**	**0.65**
			End	1.5	0.85	–	–	–	–	**0.50**	**0.60**
Common density, 40,000–60,000 plants/ha)	0.80–0.95	2.5	Ini	1.3	0.85	–	–	–	–	**0.20**	**0.30**
			Mid	1.8	0.85	–	0.81	–	–	**1.00**	**1.05**
			End	1.8	0.85	–	–	–	–	**0.95**	**1.00**
Rubber tree (*Hevea brasiliensis* L.)											
Young (<6 years)	<0.75	<8.0	Ini	1.0	1.00	–	–	–	–	**0.40**	**0.55**
			Mid	1.2	1.00	–	1.25	–	–	**0.60**	**0.75**
			End	1.1	1.00	–	–	–	–	**0.50**	**0.65**
Common density (250–350 plants/ha)	0.75–0.90	8–15	Ini	1.2	0.69	–	0.89	–	–	**0.75**	**0.85**
			Mid	1.5	0.75	–	1.10	–	–	**0.90**	**0.95**
			End	1.4	0.69	–	0.91	–	–	**0.80**	**0.85**

measured using the SWB method. Table 11 shows only the average $K_{c\ mid} = 0.82$.

Rubber tree (*Hevea brasiliensis* L.), or Pará rubber, is a tropical tree that naturally produces rubber. It is native to the tropical areas of South America, especially Brazil, but is also spread in Southeast Asia, and West Africa. The top producers are Thailand and Indonesia. Two studies were selected from the scarce literature on water use, one conducted in India (Vijayakumar et al. 1998) and the other in China (Ling et al. 2023). The planting density ranged from 250 to 400 plants/ha. Few information was available on plant height, with average $h = 11.5$ m (Ling et al. 2023), and $f_c < 0.90$. The K_c values (Table 11) show $K_{c\ mid} > 1.10$ and values for the initial and end-season stages not far from that value since it is an evergreen plantation cultivated in a rainy area.

Table 12 includes the K_c/K_{cb} values derived from the selected studies as well as the previously tabulated standard K_c and K_{cb} values available for palms and rubber trees (Allen et al. 1998; Allen and Pereira 2009; Jensen and Allen 2016; Rallo et al. 2021). These publications were the bases for the proposed standard K_c and K_{cb} values for the FAO segmented curve listed in the last two columns of the table. These standard values were derived from the previously mentioned information and using the A&P approach due to the lack of available K_c/K_{cb} information for many of the established groups of each crop. As for the other crops studied in the current review, K_c/K_{cb} values increase with increasing f_c as they are directly related to the transpiration component of ET_c, while the soil evaporation component is mainly determined by the frequency and depth of irrigation events and rainfall, and the energy available for soil water evaporation, which is limited by f_c. As noted, the plant densities and degree of ground cover values presented in Table 12 are those commonly found in commercial orchards.

Conclusions and recommendations

This review highlighted the limited number of scientific articles published after FAO56 that reported crop coefficients for many tropical and subtropical orchards and plantations. The selected studies enabled an adequate collection of well-conducted field experiments and data processing focused on the crop water requirements of these orchards and plantations. However, there is a lack of research studies on many tropical trees and shrubs, thus there is the need to improve knowledge of water management practices and efficient water use and savings without negatively impacting on the quantity and quality of yields.

Most studies used irrigation aiming at fully meeting crop water requirements, and few used regulated or sustained deficit irrigation strategies. Therefore, to improve water use and saving water, particularly in the context of climate variability and climate change, the application of deficit irrigation practices requires further knowledge and appropriate training of technicians and farm advisors to support farmers in daily decision-making. This article does not cover deficit irrigation issues but supports related further studies through providing for the know-how relative to compute crop evapotranspiration that is required for SWB studies usable for defining appropriate irrigation schedules.

The data retrieved from the selected studies combined with previously standard crop coefficients formed the basis for the proposed and tabulated standard K_c/K_{cb} values. Furthermore, the estimation of standard crop coefficients was also done using the A&P approach (Allen and Pereira 2009; Pereira et al. 2021c). This approach is based on a few field observations, f_c and h, and can provide valuable information for irrigation management and scheduling for the specific conditions of orchards and plantations. The successful application of the A&P approach to support irrigation scheduling has been described for several orchards and plantations in California using the Satellite Irrigation Management Support (SIMS) framework (Melton et al. 2018). Irrigation planning and consumptive use assessment studies at the project or watershed level may also be based on the use of standard K_c and K_{cb} or the A&P approach.

The proposed standard values for K_c and K_{cb} should be used as upper limits. It is not expected that, with few exceptions, predicting ET_c would require K_c/K_{cb} larger than the standard values. Moreover, when pursuing water savings strategies, definitely required to face water scarcity, sustained deficit irrigation should be considered, targeted, through adopting a reduction factor to the standard values for K_c and K_{cb}. It results a water saving irrigation scheduling appropriate to the orchards and plantations actual water availability conditions.

Quality control of the measured actual K_c and K_{cb} values is required. It may be performed by comparing the newly measured K_c/K_{cb} with the standard K_c/K_{cb} values tabulated in this article. If used correctly, the information will support sustainable water use, improve crop productivity and achieve progressive adaptation measures to cope with climate change. It is recommended that users study and analyze the publications herein quoted in addition to analysing the tabulated material in the current review article, namely relative to the techniques used in the cited research and to the dates and duration of the crop growth stages. There is a need to increase awareness of water conservation practices and irrigation scheduling during water scarcity and droughts, particularly based on understanding the applicability of standard crop coefficients and their transferability to other locations/climatic conditions.

Future studies should focus on high-accuracy ET_c determination of less studied crops, namely using some well-developed water and energy balance approaches. Further studies are also needed on the long-term effects of regulated deficit irrigation on crop production, as well as the use of practices to reduce non-beneficial water use, e.g., controlling soil evaporation. Fruit load and thining are expected to influence the actual K_c/K_{cb} values used for irrigation purposes, but there is not yet sufficient information on the extent of this influence, so studies on this topic are welcome.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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