Irrigation Science (2024) 42:525–539
https://doi.org/10.1007/s00271-024-00924-8

REVIEW

Mulching effects on soil evaporation, crop evapotranspiration and crop coefficients: a review aimed at improved irrigation management

Tiago B. Ramos[1] · Hanaa Darouich[2] · Luis S. Pereira[2]

Received: 10 December 2023 / Accepted: 1 March 2024 / Published online: 11 March 2024

Abstract

Mulching is a widely adopted agronomic practice, often used as a water-saving strategy due to its effectiveness in reducing soil evaporation. However, effects vary depending on the materials used and the extent of mulch soil coverage. Consequently, the impacts of mulching may differ considerably across production systems, preventing the establishment of reliable guidelines for irrigation water management. The objective of this study is to comprehensively review existing literature that compares mulching versus no-mulching management, aiming to gain a deeper understanding of the effects of mulching on soil evaporation (E_s), crop coefficients (K_c), and actual crop evapotranspiration ($ET_{c\ act}$). 58 studies were selected. The impact of mulching was particularly notable in the early crop stages, when the soil is not fully covered. Data in literature shows that plastic films were more effective in reducing K_c than organic materials. However, this effect, while evident during the early crop stages, diminished throughout the rest of the season. Black plastic films were more effective during the early crop stages compared to other colored plastics, particularly relative to the decrease of K_c, but this effect also diminishes during the rest of the season. Building upon these findings, the study provides guidelines for expected reductions in K_c values based on the type of crop, crop stage, and the mulching material most used in each cropping system.

Introduction

Mulching is an agronomic practice involving the application of a protective layer, known as mulch, to the soil surface. This layer can be made from organic materials (such as unincorporated plant residues or imported materials like straw), or inorganic materials (including plastic films, geotextiles, gravel, and crushed stones). It results in beneficial changes to the soil environment, namely improvements in physical conditions, chemical composition, and biological activities, as reviewed by Acharya et al. (2005). In terms of physical conditions, mulching significantly influences the soil moisture regime by controlling soil surface evaporation, changing soil temperature, facilitating nighttime water condensation due to temperature fluctuation, controlling soil erosion and, for non-plastic mulches, improving water infiltration, and enhancing soil water retention. As a result, mulching is often adopted in water-scarce regions for crop production, both in rainfed and irrigated areas, owing to its potential to enhance water use efficiency and save water (Pereira et al. 2009).

The benefits of organic mulches in soil water conservation are well-established, making mulching a fundamental component of Conservation Agriculture (Basch et al. 2012; Kassam et al. 2013; Jovanovic et al. 2020). Organic mulches act as a barrier to runoff and intercept raindrops, protecting the soil from splashing, particle detachment, and clogging

✉ Tiago B. Ramos
tiagobramos@tecnico.ulisboa.pt

1 Centro de Ciência e Tecnologia do Ambiente e do Mar (MARETEC-LARSyS), Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1, Lisboa 1049-001, Portugal

2 LEAF—Linking Landscape, Environment, Agriculture and Food Research Center, Associated Laboratory-TERRA, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, Lisboa 1349-017, Portugal

of surface soil pores, thereby contributing to the minimization of soil erosion (Prosdocimi et al. 2016). They enhance the macroporosity of soil structural aggregates, leading to improved water infiltration and increased soil storage capacity (Blanco-Canqui and Lal 2007; Kahlon et al. 2013). Moreover, they reduce non-beneficial water consumption by plants through decreased exposure of the soil surface to solar radiation, increased resistance to water vapor loss to the atmosphere, and the expansion of the relatively non-turbulent air zone above the soil surface, thus altering the boundary layer conditions at the soil-air interface (Acharya et al. 2005). However, the effectiveness of organic mulches much depends on the thickness and composition of the mulch (Bond and Willis 1969; Acharya et al. 2005). A thicker mulch layer produces more significant effects, and a higher carbon-to-nitrogen (C:N) ratio results in longer-lasting effects. Furthermore, rainfall interception may prevent water from infiltrating the soil surface, which may be relevant in rainfed areas where precipitation is scarce. Still, Cook et al. (2006) concluded that canopy and mulch modified the soil water balance by adversely affecting soil water content beneath thicker application but increase in soil water was much greater. Those conclusions are not enough to consider that soil water was detrimentally affected. Montenegro et al. (2013) observed that the rainfall interception by mulch was much smaller than soil water increase. Therefore, the advantages of organic mulch far outweigh these limitations.

Plastic mulches, made primarily of thin sheets of polyethylene or similar materials, are the most used inorganic mulch materials (Kasirajan and Ngouajio 2012). These sheets are typically laid over the soil surface, especially along the plant rows, with holes cut into them at plant spacings to allow the plants to emerge. The effectiveness of plastic mulch largely depends on the color of the material, which can be mainly transparent, white, or black. The color significantly impacts albedo, influencing the mulch's energy-radiating properties and affecting soil temperature in different ways (Acharya et al. 2005). This creates a microclimate around the plant by modifying the radiation budget of the surface, thus the energy balance, contributing to increased crop yields. The physical properties of soils are hardly affected since the soil may still be regularly disturbed by tillage, but changes in the soil moisture regime are evident as the plastic film acts as a barrier, preventing soil water evaporation and increasing soil moisture availability in the root zone (Kasirajan and Ngouajio 2012; Somanathan et al. 2022). The barrier evidently contributes to rainfall interception. However, as noted by Zheng et al. (2018), this effect does not overcome the positive impacts of plastic films on soil moisture conservation.

While organic and inorganic mulches have a significant impact on soil evaporation, particularly during the early stages of crop development when the plant's canopy is still small, only partially covering the ground, there is still limited understanding of the influence of different types of mulches on the crop coefficient (K_c). The single K_c represents averaged soil evaporation and crop transpiration from a cropped surface for typical frequencies of wetting (Allen et al. 1998, 2005b; Pereira et al. 2020). K_c is defined as the ratio between crop evapotranspiration (ET_c) and reference evapotranspiration (ET_o), calculated using either the FAO Penman-Monteith equation (Allen et al. 1998) or the ASCE-PM equation (Allen et al. 2005a), and it provides for an integration of the effects of key characteristics (crop height, albedo, canopy resistance, and exposed soil surface to evaporation) that differentiate a specific crop from reference grass. Therefore, since mulching can significantly reduce soil evaporation compared to what is determined under standard, best growing conditions, K_c values available in the literature (Pereira et al. 2021a, b, 2023a, b; Rallo et al. 2021) may not be useful for mulched crops if effects of mulch on K_c values are not known.

Similar reasoning applies when considering the concept of the dual K_c coefficient, that comprises the basal crop coefficient (K_{cb}) representing crop transpiration, and the evaporation coefficient (K_e) representing soil evaporation (Allen et al. 1998, 2005b). The K_e can be significantly influenced by factors such as the thickness of the organic mulch layer in the case of organic mulches or, in the case of plastic mulches, by the fraction of the ground surface that can contribute to evaporation through the vent holes in the plastic cover and the fraction of the surface that remains wet and is not covered by the mulch. The K_{cb} is not expected to be affected by mulch, yet the K_{cb} value includes a residual diffusive evaporation component supplied by soil water beneath the dry surface and from soil water beneath dense vegetation (Allen et al. 1998). Furthermore, the increased water availability resulting from reduced soil evaporation may lead to greater crop transpiration, particularly in crops grown under non-optimal management.

Allen et al. (1998) proposed a set of general guidelines to modify the tabulated K_c (and K_{cb}) values for different crop stages based on the type of mulch, soil coverage, and the quantity of organic mulch applied. However, compared with present conditions, information at that time was rather limited. Therefore, those guidelines, while informative, are often deemed overly generic for practical applications (Odhiambo and Irmak 2012). Hence, the objective of this study is to review the existing literature regarding studies that compare mulching vs. no-mulching management to gain a deeper understanding of the impacts of mulching on crop coefficients.

Materials and methods

The review aimed at collecting data on the effects of mulching on actual crop coefficients ($K_{c\ act}$), soil evaporation (E_s), and actual crop evapotranspiration ($ET_{c\ act}$) of field, vegetable, and trees and vine crops. A total of 58 studies were selected (a much larger number of papers report on using mulch but do not allow comparing appropriately with no-mulch conditions). The search was performed using journals data repositories (Elsevier, Wiley, Springer, CSIRO publishing, Scielo), Google Scholar as well as using the reference lists of selected articles. Keywords included terms such as mulch, mulching, surface mulch, mulch versus no mulch, organic mulching, plastic film, crop coefficients, soil evaporation, and crop evapotranspiration. Various languages were used for the search (English, Portuguese, Spanish, French, Italian, and German). No restrictions regarding studies' location or year of publication were considered. Only full articles were reviewed. The criteria used for selecting the papers from which data was collected followed similar reviews on K_c and ET data (Pereira et al. 2021a, b, 2023a, b; Rallo et al. 2021) and included the following:

(a) The papers should be of good or acceptable quality, regardless of the journal in which they were published.
(b) The field and computation methods should be comprehensively described and easily understandable for any interested reader. They should reference consistent methodologies for calculating E_s and $ET_{c\ act}$, preferably in accordance with Allen et al. (2011).
(c) The studies should compare the effects of mulching on $K_{c\ act}$, E_s, and/or $ET_{c\ act}$ data obtained in well-defined treatment plots. A control treatment should consider bare soil conditions.
(d) The type of mulch should be well identified. In the case of organic mulching, the amount of material should be provided. In the case of inorganic mulching, the characteristics of the material used should be preferable given, as well as the faction of surface mulched.
(e) For K_c data, the FAO56 Penman Monteith (PM) equation (Allen et al. 1998) or the ASCE-PM equation (Allen et al. 2005a) should be used to compute reference evapotranspiration (ET_o).
(f) The K_c data should adhere to the physical constraints of the surface energy balance process. The latent heat flux (λE), representing the energy available for the evaporation process and derived from the net radiation flux (R_n) minus soil heat flux (G) and sensible heat flux (H), shows upper limits for K_c values of 1.2 in sub-humid regions and 1.2–1.4 in arid regions (both referenced to grass). Values exceeding these limits may result from errors in ET measurement, weather data used for ET_o calculation, or data processing procedures (Allen et al. 2011; Pereira et al. 2021a), and related papers were therefore not considered.
(g) In studies comparing various irrigation treatments, only data from the fully irrigated plots were taken into consideration.
(h) When not explicitly reported in the text, data for $K_{c\ act}$, E_s, and $ET_{c\ act}$ were extracted from tables and graphics.

The majority of field research methods followed a soil–water balance (SWB) approach based on observations of the soil water content (SWC) using soil sampling or various types of sensors, the eddy covariance system, and weighing and drainage lysimeters for measuring ET fluxes. Mini or micro lysimeters were also commonly used to measure soil evaporation. Less frequently, the Bowen ratio energy balance was used for measuring ET, and sap flow techniques for assessment of crop transpiration. Most of these field methods, along with their accuracy analyses, are comprehensively described by Allen et al. (2011). Models were not commonly employed in the analysis of mulching effects on K_c and ET data. The SIMDualKc (Rosa et al. 2012; Pereira et al. 2020) and Aquacrop (Vanuytrecht et al. 2014) models were the few exceptions.

K_c values were collected and categorized into three groups: early stages ($K_{c\ early}$), mid-season ($K_{c\ mid}$), and late and end season ($K_{c\ late}$). Conversions were inevitably made for studies reporting data for crop phenological stages. The early stages corresponded to the traditional initial and crop development stages as defined in Allen et al. (1998), therefore extending from sowing (for field crops), planting (for vegetable crops), or bud burst (for trees and vines) until the time before the plant's canopy reaches its maximum coverage. During these early stages, the soil surface remained fully or partially exposed, soil evaporation rates were at their maximum, and the effect of mulching was expectably more significant. The definition of initial crop stage (Allen et al. 1998) could not be adopted because it was not followed by many authors. The mid-season was defined as in Allen et al. (1998), corresponding to the period with maximum ET and maximum canopy coverage. The late and end season included all K_c data measured during crop senescence, not just when the crop was fully matured and ready for harvest as the K_c value for the end season ($K_{c\ end}$) in Allen et al. (1998) implies. For each study, K_c data from different seasons was averaged to have a single value for each crop stage.

Likewise, E_s and $ET_{c\ act}$ data were collected and sorted into the same three stage groups as the K_c data, when possible, or presented as seasonal values when no distinction was presented. Those values from various seasons and treatments were subjected to averaging. Since data was available either in cumulative terms for a specific crop stage or as daily averages, it was processed in relative terms, indicating the percentage increase or decrease of E_s and $ET_{c\ act}$ in the mulching treatment compared to control bare soil plots.

Results and discussion

Results from literature review

Effects of mulching on soil evaporation

Table 1 presents the average relative variation (expressed in percentage values) in soil evaporation reported in studies comparing the effectiveness of mulch treatments to no mulch. While soil evaporation is the primary component of the soil water balance influenced by mulching, it is notable that there is a very limited number of available studies addressing this issue, primarily focused on field crops such as wheat, maize, sorghum, cotton, and potato. Predominantly, the organic materials used for mulching included wheat, maize, oat, and rice straws, with amount of straw ranging from 1.0 to 18.0 tonnes/ha, and surface soil coverage varying from 67 to 100%. The significant variation in crop residue rates was first reported by Adams et al. (1976), wherein they examined the effects of different residue rates (ranging from 1.0 to 10.0 tonnes/ha) on soil evaporation in a sorghum field irrigated by sprinklers. Klocke et al. (2009) considered the highest residue rates, averaging 15.0 to 18.0 tonnes/ha, in their study aimed at measuring soil evaporation from bare soil and soil covered with either corn stover or standing wheat stubble beneath the canopy of maize. No other study applied such high rates. Plastic film was the predominant inorganic mulching material used, typically positioned along the crop rows and covering 60–80% of the soil surface. An exception to this practice was found in the study by Zhang et al. (2018a), where they applied subsoil mulching by burying the plastic film 0.1 m deep. Unfortunately, not all studies offered a thorough characterization of the plastic film used, with many not indicating plastic color and thickness.

All studies documented a decrease in soil evaporation at various stages of crop growth due to mulching. The influence of soil mulching on soil evaporation was naturally more prominent in the earlier stages of crop growth, when the crop's canopy was still small, and the energy available at the soil surface for soil evaporation was at its maximum. During these early stages, the differences in cumulative values observed between mulch and no-mulch treatments ranged from 4 to 53 mm, with an average of 25 mm across the different studies. In the mid-season and late-season stages, these differences were narrower, ranging from 1 to 33 mm (with an average of 14 mm) and from 1 to 25 mm (with an average of 7 mm), respectively. Still, there was always a decrease of soil evaporation rates in mulch treatments compared to no-mulch. In relative terms, the effect of mulching on soil evaporation during the different crop stages was less noted, as reductions of smaller absolute values can yield higher relative values. As a result, percentage reductions averaged 40% in the early crop stages, 35% in the mid-season, and 33% in the late season stage. Nevertheless, the seasonal data in Table 1 unambiguously demonstrate that mulching significantly contributes to decreasing soil evaporation, with percentage reductions ranging from 17% (Yan et al. 2018) to 79% (Tian et al. 2016) over the course of a full season. However, the extreme value of the range is quite uncommon as achieving complete efficiency in reducing soil evaporation during the late season stage, as reported in Tian et al. (2016), is rare especially when soil coverage is not total.

Despite the limited number of available studies, it is possible to observe in Table 1 that factors such as the crop residue rate and the type of material used for mulching significantly influenced the rate of soil evaporation reduction in agreement with Bond and Willis (1969). Adams et al. (1976) remains the most substantial study evaluating the impact of different crop residue rates on soil evaporation. Their findings indicated an average reduction ranging from 27 to 78% for oat straw rates varying from 1.0 to 10.0 tonnes/ha. Surprisingly, no subsequent studies were conducted anywhere in the world to corroborate those findings by extending them to different crops, climates, soils, and water management practices. The exception may be Yan et al. (2018), who examined various residue rates (4.5 and 9.0 tonnes/ha) and different soil coverage ratios (67% and 100%). Although the influence of residue rate on the reduction of soil evaporation was evident, the effect of soil coverage was not significant.

In terms of the type of mulch, Table 1 reveals that soil evaporation reductions averaged 30–35% in studies using straw mulch and 38–47% in studies using plastic mulching. Likely, it appears that plastic film is more effective in reducing soil evaporation rates. However, it is important to note that, based on the criteria outlined in Sect. 2, no study was found that compared the performance of these two types of mulch under the same conditions, thus it is not sure that plastic mulch is really superior and for which conditions this may occur. Furthermore, no study was found evaluating the impact of plastic color on soil evaporation, and the data from Table 1 is insufficient to draw any conclusive findings on this matter.

Table 1 Average variation (%) of soil evaporation (E_s) in mulched plots compared to non-mulched plots

Crop name	Mulch			E_s variation (%)				Reference
	Type	Amount (tonnes/ha)	% cover	Early stages	Mid-season	Late & end season	Full season	
Field crops								
Wheat	Maize straw	5.5	100	-	-	-	-28	Wang et al. (2018)
	Maize straw	6.0	100	-31	-37	-20	-33	Zhang et al. (2003)
	Maize straw	3.0	100	-38	-26	-33	-32	Cheng et al. (2021)
	Maize straw	6.0	100	-48	-44	-50	-47	
	Maize straw	4.5	100	-15	-21	-24	-17	Yan et al. (2018)
	Maize straw	9.0	100	-38	-34	-41	-32	
	Maize straw	4.5	67	-26	-19	-17	-24	
	Maize straw	9.0	67	-46	-36	-34	-38	
	Film	-	100	-	-	-	-48	Wen et al. (2017)
	Buried film	-	97	-29	-18	-33	-27	Zhang et al. (2018a)
Maize	Wheat straw	6.0	100	-41	-32	-17	-36	Zhang et al. (2003)
	Wheat straw	15.0	94	-	-	-	-44	Klocke et al. (2009)
	Maize straw	18.0	99	-	-	-	-49	
	Black film	-	60	-60	-29	-36	-42	Chen et al. (2019)
	Transparent film	-	77	-38	-33	-31	-45	Zhang et al. (2018b)
	Transparent film	-	100	-	-	-	-47	Lin et al. (2019)
	Film	-	80	-38	-38	-22	-35	Feng et al. (2019)
	Film	-	60	-11	-28	-28	-28	Gong et al. (2017)
	Film	-	70	-44	-57	-32	-44	Shen et al. (2019)
	Film	-	60*	-79	-43	-16	-59	Jia et al. (2021)
Sorghum	Oat straw	1.0	100	-	-	-	-27	Adams et al. (1976)
	Oat straw	4.0	100	-	-	-	-58	
	Oat straw	10.0	100	-	-	-	-78	
Cotton	Transparent film	-	60	-	-	-	-32	Han et al. (2019)
	Film	-	76	-56	-93	-100	-79	Tian et al. (2016)
Potato	Rice straw	6.3	100	-	-	-	-66	Brar et al. (2019)
Trees and vines								
Apple	Horticultural fabric	-	-	-	-14	-	-	Liao et al. (2021)
	Maize straw	-	-	-	-36	-	-	

* Measurements taken in plastic cover area, thus value of soil coverage may not be representative of actual conditions

Effects of mulching on crop coefficients

Table 2 presents the single K_c values observed during the early ($K_{c\ early}$), mid-season ($K_{c\ mid}$), and late-season ($K_{c\ late}$) crop stages in studies comparing the effectiveness of mulch treatments to no mulch. Data is available for various types of crops, including field crops (wheat, maize, sorghum, cotton, sugarcane, okra, and peanut), vegetables (squash, cucumber, tomato, onion, banana, and curcuma), as well as trees and vines (pear, apricot, and grapevine). More studies were available compared to those addressing soil evaporation, totaling 21 studies. Crop residues now further include sugarcane tops and leaves. Furthermore, a greater number of studies provide a more comprehensive characterization of the plastic films used.

The K_c values in Table 2 refer to the actual K_c ($K_{c\ act}$) as they reflect different crop and irrigation management practices. Therefore, the listed $K_{c\ act}$ includes the coefficient K_s ($K_{c\ act} = K_c\ K_s$), which is defined for water and salinity stress, and may range from 0 to 1, with its maximum corresponding non-stress conditions. The use of the K_s coefficient under mulch conditions is widely reported in the literature (Liu et al. 2022a, b; Petry et al. 2023, 2024). However, in this review it was not possible to distinguish the stress component of the $K_{c\ act}$, either because many comparisons were held under full irrigation conditions (thus, K_s=1) or data was insufficient to evaluate the degree of crop stress.

In many studies, the reported $K_{c\ act}$ values in Table 2 for non-mulch conditions seem to exhibit some degree of abiotic stress (most likely water stress) as they are substantially lower than the tabulated K_c values found in Allen et al. (1998) or the updates provided in Pereira et al. (2021a, b) for field and vegetable crops, and in Rallo et al. (2021) Pereira et al. (2023b) for trees and vines. In other studies, K_c values for non-mulched conditions are very close to those proposed in the above cited literature, suggesting better

Table 2 Crop coefficients (K_c) in mulched plots compared to non-mulched plots

Crop name	Mulch			K_c values						Reference
				Early stages		Mid-season		Late & end season		
	Type	Amount (tonnes/ha)	% cover	mulch	No-mulch	mulch	No-mulch	mulch	No-mulch	
Field crops										
Wheat	Maize straw	5.5	100	0.72	0.73	1.13	1.15	0.70	0.75	Wang et al. (2018)
Maize	Film	-	80	0.34	0.40	0.97	1.01	0.93	0.94	Feng et al. (2019)
	Film	-	60	0.22	0.27	0.91	1.01	0.94	0.99	Gong et al. (2017)
	Film	-	-	0.29	0.30	1.09	1.20	0.61	0.65	Guo et al. (2020)
	Film	-	70	0.38	0.52	1.17	1.21	0.79	0.94	Shen et al. (2019)
	Black film	-	60	0.38	0.55	0.87	0.92	0.43	0.65	Chen et al. (2019)
	Transparent film	-	77	0.28	0.37	1.13	1.12	0.65	0.70	Zhang et al. (2018b)
Cotton	Transparent film	-	60	0.27	0.32	0.99	0.98	0.37	0.44	Han et al. (2019)
	Black film	-	-	0.31	0.55	0.89	1.06	0.44	0.45	Prajapati and Subbaiah (2019)
	Film*	-	-	0.32	0.55	0.91	1.06	0.45	0.45	
	Wheat straw	-	-	0.35	0.55	0.97	1.06	0.45	0.45	
Sugarcane	Cane tops	1.8	55	0.26	0.32	1.01	1.12	0.80	1.08	Olivier and Singels (2012)
	Tops & leaves	10.4	98	0.18	0.32	0.93	1.12	1.00	1.08	
Okra	Black film	-	-	0.37	0.62	0.77	0.93	0.48	0.53	Patil and Tiwari (2018)
Peanut	Rice straw	5.0	100	0.45	0.68	0.76	0.88	0.52	0.71	Zayton et al. (2014)
Vegetables										
Squash	Transparent film	-	-	0.23	0.33	0.44	0.53	0.50	0.50	Hassan and Magdy (2014)
	Black film	-	-	0.26	0.33	0.47	0.53	0.44	0.50	
Cucumber	Transparent film	-	-	0.14	0.15	0.45	0.61	0.35	0.43	Yaghi et al. (2013)
	Black film	-	-	0.13	0.15	0.49	0.61	0.36	0.43	
Tomato	Rice straw	2.0	100	0.64	0.70	0.99	1.07	0.71	0.78	Zakari et al. (2019)
	Wood shaving	3.6	100	0.60	0.70	0.94	1.07	0.69	0.78	
	White film	-	-	0.53	0.70	0.86	1.07	0.62	0.78	
Onion	Rice straw	5.6	-	0.51	0.59	1.02	1.04	0.76	0.74	Igbadun and Oiganji (2012)
	Black film	-	-	0.50	0.59	1.03	1.04	0.77	0.74	
	Transparent film	-	-	0.50	0.59	1.04	1.04	0.72	0.74	
Curcuma	Black film	-	100	0.24	0.43	0.94	1.10	0.81	0.95	Santosh et al. (2021)
Banana	Black film	-	-	0.57	0.82	0.95	1.10	0.95	1.10	Santosh and Tiwari (2023)
Trees and vines										
Pear	Black film	-	-	0.51	0.71	0.74	0.95	0.43	0.54	Eid and Abou Grah (2012)
	Rice straw	-	100	0.53	0.71	0.78	0.95	0.46	0.54	
	Weed cutting	-	-	0.61	0.71	0.87	0.95	0.47	0.54	
Apricot	Black film	-	-	0.39	0.68	0.62	0.82	0.37	0.53	El-Naggar et al. (2018)
	White film	-	-	0.43	0.68	0.66	0.82	0.39	0.53	
	Rice straw	-	100	0.45	0.68	0.68	0.82	0.44	0.53	
Vineyard	Pruning waste	-	-	-	-	0.37	0.46	-	-	López-Urrea et al. (2020)
	Film	-	-	-	-	0.32	0.46	-	-	

* Biodegradable

management of irrigation water in those experiments. These are, for example, the $K_{c\ mid}$ values for winter wheat in the study by Wang et al. (2018), maize in Guo et al. (2020) and Shen et al. (2019), okra in Patil and Tiwari (2018), and onion in Igbadun and Oiganji (2012). When it comes to trees and vines, comparing K_c values is not as straightforward as it is for field crops and vegetables. This difficulty arises from the various factors known to influence crop evapotranspiration in orchard systems, including planting density, tree height, training system, canopy cover, irrigation method, and inter-row management. Unfortunately, many of the reviewed studies did not provide sufficient information on these parameters for a more comprehensive comparison.

Mulching resulted in an overall reduction of the K_c values compared to those obtained under no-mulch conditions, as depicted in Table 3. The only exceptions were the $K_{c\ mid}$ values for maize and cotton as reported by Zhang et al. (2018b); Han et al. (2019), respectively, and the $K_{c\ late}$ values for onion provided by Igbadun and Oiganji (2012). These values were slightly higher under mulch treatments, albeit with minimal differences compared to the no-mulch treatments. A possible explanation for this phenomenon may be the increase of the transpiration component in response to the increase of water availability resulting from the reduction in soil evaporation. For all the rest, the K_c values under mulch directly translated the reduction of the soil evaporation component. The reduction in K_c values was typically more pronounced during the early crop stages, ranging from a 1.4% decrease in wheat, as reported by Wang et al. (2018), to a 43.5% reduction in curcuma, according to Santosh et al. (2021). The reduction in $K_{c\ early}$ values was lower in organic mulch plots (averaging 22%) than in plastic film plots (averaging 26% reduction). More pronounced differences emerged when accounting for the color of the plastic. The black film showed an average reduction of 31%, while plots

Table 3 Average variation (%) of crop coefficients (K_c) in mulched plots compared to non-mulched plots

Crop name	Mulch			K_c variation (%)			Reference
	Type	Amount (tonnes/ha)	% cover	Early stages	Mid-season	Late & end season	
Field crops							
Wheat	Maize straw	5.5	100	-1.4	-1.9	-5.8	Wang et al. (2018)
Maize	Film	-	80	-15.1	-4.5	-1.1	Feng et al. (2019)
	Film	-	60	-18.5	-9.9	-5.1	Gong et al. (2017)
	Film	-	-	-3.3	-9.2	-6.2	Guo et al. (2020)
	Film	-	70	-26.9	-3.3	-16.0	Shen et al. (2019)
	Black film	-	60	-30.9	-5.4	-34.6	Chen et al. (2019)
	Transparent film	-	77	-24.1	0.6	-7.6	Zhang et al. (2018b)
Cotton	Transparent film	-	60	-15.6	1.0	-15.9	Han et al. (2019)
	Black film	-	-	-43.1	-16.0	-2.2	Prajapati and Subbaiah (2019)
	Film*	-	-	-42.2	-14.2	0.0	
	Wheat straw	-	-	-36.7	-8.5	0.0	
Sugarcane	Cane tops	1.8	55	-19.0	-9.8	-25.6	Olivier and Singels (2012)
	Tops & leaves	10.4	98	-42.9	-17.0	-7.0	
Okra	Black film	-	-	-40.7	-17.2	-9.4	Patil and Tiwari (2018)
Peanut	Rice straw	5.0	100	-33.8	-13.6	-26.2	Zayton et al. (2014)
Vegetables							
Squash	Transparent film	-	-	-30.3	-17.0	0.0	Hassan and Magdy (2014)
	Black film	-	-	-21.2	-11.3	-12.0	
Cucumber	Transparent film	-	-	-6.7	-26.2	-18.6	Yaghi et al. (2013)
	Black film	-	-	-13.3	-19.7	-16.3	
Tomato	Rice straw	2.0	100	-8.6	-7.5	-9.0	Zakari et al. (2019)
	Wood shaving	3.6	100	-14.3	-12.1	-11.5	
	White film	-	-	-24.3	-19.6	-20.5	
Onion	Rice straw	5.6	-	-13.6	-1.9	2.7	Igbadun and Oiganji (2012)
	Black film	-	-	-15.3	-1.0	4.1	
	Transparent film	-	-	-15.3	-0.0	-2.7	
Curcuma	Black film	-	100	-43.5	-14.5	-14.7	Santosh et al. (2021)
Banana	Black film	-	-	-30.6	-13.4	-13.4	Santosh and Tiwari (2023)
Trees and vines							
Pear	Black film	-	-	-28.9	-22.0	-19.5	Eid and Abou Grah (2012)
	Rice straw	-	100	-24.9	-18.2	-14.8	
	Weed cutting	-	-	-13.8	-8.6	-12.5	
Apricot	Black film	-	-	-42.6	-24.9	-30.3	El-Naggar et al. (2018)
	White film	-	-	-36.3	-19.1	-25.9	
	Rice straw	-	100	-33.6	-16.7	-17.5	
Vineyard	Pruning waste	-	-	-	-19.7	-	López-Urrea et al. (2020)
	Film	-	-	-	-29.9	-	

* Biodegradable

with white films exhibited a 30% reduction in $K_{c\ early}$. Transparent plastics were found to be relatively less effective in reducing $K_{c\ act}$ values, demonstrating an average reduction of 18%. For the remaining crop stages, differences in terms of plastic materials compared to organic materials were less pronounced. Nevertheless, it should be noted that the discrepancies found in the plastic color was not evident when the comparison was conducted under the same conditions, as demonstrated by Hassan and Magdy (2014) in the case of squash and Yaghi et al. (2013) in the case of cucumber.

Effects of mulching on actual evapotranspiration

Table 4 shows the average relative variation (expressed in percentage values) in actual crop evapotranspiration ($ET_{c\ act}$) estimates reported in studies comparing the effectiveness of mulch treatments to no mulch. Undoubtedly, the $ET_{c\ act}$ was the parameter that received the most extensive evaluation in that comparison, involving a total of 52 different studies. The available data comprises estimates for a wide range of crops, including field crops (wheat, barley, maize, cotton, sugarcane, potato, okra, and peanut), vegetables (squash, cucumber, cabbage, tomato, bean, onion, rapeseed, chard, curcuma, strawberry, and watermelon), as well as trees and vines (pear, apricot, jujube, and grapevine). The organic materials used as mulch include maize, wheat, and rice straws, sugarcane residues, Egyptian clover, weeds residues, and vines pruning. Plastic films used were black, white, and transparent. 14 studies directly compared the effect of organic and inorganic materials (e.g., Li et al. 2013; Zhang et al. 2011; Prajapati and Subbaiah 2019) on $ET_{c\ act}$. Likewise, 10 studies compared the impact of plastic colors (e.g., Hassan and Magdy 2014; Yaghi et al. 2013; Igbadun and Oiganji 2012; El-Naggar et al. 2018) on $ET_{c\ act}$.

Consistent with E_s and the K_c analysis, $ET_{c\ act}$ values exhibited a more pronounced reduction during the earlier crop stages due to decreased soil evaporation when comparing the results from mulch-treated plots with those from non-mulch plots. In the crop earlier stages, the reduction of $ET_{c\ act}$ due to mulching averaged 23% in all plots, with organic mulch plots exhibiting lower decrease (17%) than plastic film plots (27%). No significative differences were found relative to the effectiveness of plastic color in this context since $ET_{c\ act}$ average reductions ranged from 27% in white film mulched plots to 29% in black film mulched plots. This is primarily due to conflicting reports in the literature, as Hassan and Magdy (2014) and Yaghi et al. (2013) presented more favorable results for plots with transparent plastic, while Igbadun and Oiganji (2012) reported a more efficient effect with black films.

A reduction in $ET_{c\ act}$ values was also observed during the mid-season and late stages, although to a lesser extent when compared to the earlier crop stages. Consequently, seasonal reductions in $ET_{c\ act}$ values were more moderate, averaging 13% across all mulching plots, 11% in organic mulching plots, and 15% in plastic mulching plots. The color of the plastic film had no apparent effect on $ET_{c\ act}$, except in the case of transparent films.

Several authors (e.g., Zhang et al. 2011, 2018a; Li et al. 2013; Shen et al. 2019; Chen et al. 2019; Wang et al. 2023) presented findings that contradict the general dynamics described above. They reported higher $ET_{c\ act}$ estimates for the mid-season and, less frequently, for the late-season in mulch plots compared to no-mulch plots. These studies primarily pertain to rainfed or irrigated wheat or maize systems, and as explained in these studies, the increased water availability resulting from the reduction of soil evaporation was subsequently used in the transpiration process. This conclusion appears reasonable, especially when considering that the K_c values reported in some of these studies were notably lower than the standard values for wheat and, particularly, maize grown under pristine conditions. While differences in seasonal $ET_{c\ act}$ values between mulch and no-mulch plots were very small for most cases, there are others where those differences were large (e.g., Chang et al., 2020; Wang et al., 2023). Reasons for this are unclear.

Effect of mulch on crop evapotranspiration

Based on the literature reviewed in the previous sections, Table 5 summarizes the average effects of mulch materials on E_s, $K_{c\ act}$, and $ET_{c\ act}$ values reported during the early, mid-season, and late-season crop stages. For each parameter and type of mulching material, a range of values is established, determined by the first and third quartiles of the data collected in the literature review. The intervals provided for different materials often overlap in many cases due to the various, and at times contradictory, effects reported in the literature. In certain instances, the available data is too limited for the intended purpose. Nevertheless, as referred above, the impact of mulching is particularly notable in the early crop stages when the soil is not fully covered, as compared to the other stages. This was to be expected as the energy available for soil evaporation is likely at its maximum during the early crop stages, when plant's canopy is still small. Plastic films are more effective in reducing E_s, $K_{c\ act}$, and $ET_{c\ act}$, especially during the early crop stages when compared to organic materials. However, this effect diminishes during the rest of the season. In terms of color, black plastic films seem also more effective during the early crop stages compared to other colored plastics, particularly for the $K_{c\ act}$. However, the impact of plastic color remains subjected to some uncertainty due to contradictory studies

Table 4 Average reductions (%) of actual crop evapotranspiration ($ET_{c\ act}$) in mulched plots compared to non-mulched plots

Crop name	Organic mulch			$ET_{c\ act}$ variation (%)				Reference
	Type	Amount (tonnes/ha)	% cover	Early stages	Mid-season	Late & end season	Full season	
Field crops								
Wheat	Maize straw	5.5	100	-	-	-	-4	Wang et al. (2018)
	Maize straw	3.0	100	-	-	-	-4	Cheng et al. (2021)
	Maize straw	6.0	100	-	-	-	-6	
	Maize straw	4.5	100	-	-	-	-14	Yan et al. (2018)
	Maize straw	9.0	100	-	-	-	-20	
	Maize straw	4.5	67	-	-	-	-11	
	Maize straw	9.0	67	-	-	-	-18	
	Maize straw	6.0	100	-	-	-	6	Yang et al. (2020)
	Maize straw	8.0	100	-	-	-	2	Adil Rashid et al. (2019)
	Maize straw	9.0	55	-	-	-	2	Chai et al. (2022)
	Transparent film	-	100	-	-	-	3	
	Rice straw	2.0	100	-	-	-	-2	Ram et al. (2013)
	Rice straw	4.0	100	-	-	-	-4	
	Rice straw	6.0	100	-	-	-	-5	
	Rice straw	8.0	-	-	-	-	-16	Chakraborty et al. (2008)
	Transparent film	-	-	-	-	-	-12	
	Black film	-	-	-	-	-	-10	
	Leucaena leaves	2.0	100	-	-	-	5	Sharma et al. (1998)
	Leucaena leaves	4.0	100	-	-	-	6	
	Leucaena leaves	6.0	100	-	-	-	9	
	Film	-	100	-	-	-	-5	Wen et al. (2017)
	Film	-	100	-	-	-	4	Li et al. (2004)
	Buried film	-	97	-21	18	3	2	Zhang et al. (2018a)
Barley	Rice straw	5.0	100	-	-	-	8	Sarkar and Singh (2007)
Maize	Film	-	-	-4	12	-15	1	Li et al. (2013)
	Wheat straw	-	-	-1	7	-10	1	
	Wheat straw	4.5	100	-	-	-	-3	Zhang et al. (2011)
	Wheat straw	15.0	94	-	-	-	0	Klocke et al. (2009)
	Maize straw	18.0	99	-	-	-	0	
	Maize straw	4.6	83	-14	-11	60	-6	van Donk et al. (2010)
	Maize straw	6.0	100	-	-	-	-5	Lu et al. (2014)
	White film	-	50	-	-	-	4	Zhang et al. (2011)
	Wheat straw + white film	2.3	50 + 50	-	-	-	2	
	Black film	-	60	-38	3	13	-8	Chen et al. (2019)
	Transparent film	-	77	-	-	-	-4	Zhang et al. (2018b)
	Transparent film	-	100	-	-	-	-5	Lin et al. (2019)
	Transparent film*	-	100	-	-	-	0	Wang et al. (2021)
	Black film*	-	100	-	-	-	0	
	Transparent film	-	100	-	-	-	-3	
	Black film	-	100	-	-	-	-5	
	Film	-	80	-22	-5	5	-8	Feng et al. (2019)
	Film	-	60	-	-	-	-9	Gong et al. (2017)
	Film	-	70	-31	18	-23	-2	Shen et al. (2019)
Cotton	Transparent film	-	60	-	-	-	-3	Han et al. (2019)
	Film	-	76	-26	-19	-2	-16	Tian et al. (2016)
	Black film	-	-	-	-	-	-15	Prajapati and Subbaiah (2019)
	Film	-	-	-	-	-	-13	
	Wheat straw	-	-	-	-	-	-9	
Sugarcane	Cane tops	1.8	55	-	-	-	-17	Olivier and Singels (2012)
	Tops & leaves	10.4	98	-	-	-	-17	

Table 4 (continued)

Crop name	Organic mulch			$ET_{c\ act}$ variation (%)				Reference
	Type	Amount (tonnes/ha)	% cover	Early stages	Mid-season	Late & end season	Full season	
Potato	Rice straw	6.3	100	-	-	-	-3	Brar et al. (2019)
	Maize straw	-	50	-9	26	-12	2	Chang et al. (2020)
	Black film	-	58	5	11	-16	7	
	Black film	-	92	1	18	3	4	
Okra	Black film	-	-	-35	-19	-11	-21	Patil and Tiwari (2018)
	Rice straw	5.0	100	-	-	-	-1	Patra et al. (2023)
	Black film	-	100	-	-	-	1	
Peanut	Rice straw	5.0	100	-53	-13	-24	-30	Zayton et al. (2014)
Vegetables								
Squash	Transparent film	-	-	-47	-2	-24	-16	Hassan and Magdy (2014)
	Black film	-	-	-33	1	-19	-11	
Cucumber	Transparent film	-	-	-23	-11	-18	-13	Yaghi et al. (2013)
	Black film	-	-	-18	-11	-18	-13	
Cabbage	Rice straw	11.0	95	-	-	-	-1	Biswas et al. (2022)
	Egyptian clover	-	80	-	-	-	-6	
Tomato	Rice straw	2.0	100	-8	-8	-8	-8	Zakari et al. (2019)
	Wood shaving	3.6	100	-14	-12	-12	-12	
	White film	-	-	-24	-19	-20	-21	
	Rice straw	5.0	50	-	-	-	-5	Mukherjee et al. (2010)
	White film	-	50	-	-	-	-6	
	Black film	-	50	-	-	-	-6	
	Black film	-	100	-	-	-	-17	Karaer et al. (2023)
Bean	Wheat straw	7.0	100	-	-	-	-8	Barros and Hanks (1993)
Onion	Rice straw	5.6	-	-11	-2	4	-3	Igbadun and Oiganji (2012)
	Black film	-	-	-14	0	-3	-5	
	Transparent Film	-	-	-13	-1	4	-4	
	White film	-	-	-	-	-	-14	Shanono et al. (2022)
Rapeseed	Film	-	-	-	-	-	26	Wang et al. (2023)
	Film*	-	-	-	-	-	22	
	Maize straw	9.5	-	-	-	-	9	
Chard	Rice straw	-	-	-	-	-	-13	Zhang et al. (2009)
	Gravel	-	-	-	-	-	-26	
Curcuma	Black film	-	100	-32	-15	-15	-22	Santosh et al. (2021)
Strawberry	Transparent film	-	-	-	-	-	2	Ayas (2023)
	Black film	-	-	-	-	-	3	
Watermelon	Transparent film	-	-	-	-	-	-20	Ghawi and Battikhi (1986)
	Black film	-	-	-	-	-	-34	
Trees and vines								
Pear	Black film	-	-	-29	-23	-10	-23	Eid and Abou Grah (2012)
	Rice straw	-	100	-25	-19	-6	-19	
	Weed cutting	-	-	-14	-10	-3	-10	
Apricot	Black film	-	-	-35	-25	-31	-29	El-Naggar et al. (2018)
	White film	-	-	-30	-19	-26	-23	
	Rice straw	-	100	-26	-17	-18	-20	
Jujube	Film	-	20	-22	-13	-13	-14	Sun et al. (2012)
	Maize straw	7.5	100	-9	-2	-7	-5	
Vineyard	Pruning waste	-	-	-	-	-	-17	López-Urrea et al. (2020)
	Film	-	-	-	-	-	-27	

* Biodegradable

Table 5 Approximate reductions (%) of soil evaporation (E_s), crop coefficients (K_c) and actual crop evapotranspiration ($ET_{c\ act}$) based on first and third quartiles of the data collected in literature reporting straw and plastic film mulch relative to no mulch

Parameter reduction	Mulch material	Early stages (%)	Mid-season (%)	Late & end season (%)
E_s	Straw	30–42	26–36	19–36
	Plastic film	38–58	31–51	25–34
K_c	Straw	14–34	8–17	8–17
	Plastic film	15–35	9–20	5–19
	Black	23–43	12–19	12–20
	Transparent	15–24	9–22	3–16
	White	27–33	-*	22–25
$ET_{c\ act}$	Straw	9–14	8–13	7–14
	Plastic film	22–32	7–19	13–21
	Black	26–35	12–22	11–18
	Transparent	18–35	-*	20–23
	White	26–29	-*	22–25

* Not given due to limited data

Table 6 Approximate reductions (%) in K_c for various field and horticultural crops under nearly full plastic mulch and organic mulch relative to using no mulch when irrigation is by trickle irrigation

Crop	Early vegetative stages (%)	Mid-season (%)	Late and end season (%)	Notes
Field crops (maize, sorghum, wheat, okra, peanut, etc.)	5–25	5–10	5–25	Plastic films
Cotton	15–35	5–10	5–15	Plastic and straw
Sugar cane	15–35	10–15	10–20	Organic mulch
Vegetables (banana, cucumber, curcuma, onion, tomato, etc.)	10–35	5–10	5–10	Plastic and straw
Fruit tree and vine crops (apricot and pear orchards, and grapes vineyards)	15–35	10–25	10–25	Both plastic and organic mulches

Note upper limits of the ranges apply when film mulch largely covers the soil or when organic mulch is dense and extensive and $ET_{c\ act}$ equals or exceeds pristine crop ET_c

assessing it under similar conditions. The effect of plastic color also diminishes during the rest of the season.

Table 6 further revises the general guidelines proposed by Allen et al. (1998) for expected reductions of K_c values based on the available information. The guidelines are given as range values and consider different crops, crop stages, and the preferred material used for mulching. For the case of organic mulching, it is still not possible to include the effects of residue rates in the guidelines due to lack of information. Selecting the values to use from the proposed ranges should be made with care as they represent approximative average effects related to the crop-soil conditions that determine the non-mulch K_c. Lower values of the ranges correspond to crop-soil conditions that refer to low non-mulch $K_{c\ act}$ and to low soil cover and/or degraded mulch while the upper limits of the range concern non-mulch high $K_{c\ act}$, namely when influenced by local and/or regional advection and when the mulch largely covers the soil and its amount is large in case of organic mulch. Users are invited to develop their own guidelines based on those proposed herein.

Conclusions

This study systematically reviewed 58 research articles comparing mulching versus no-mulching management in various cropping systems. The primary aim was to deepen our understanding of the effects of this agronomic practice on soil evaporation (E_s), crop coefficients (K_c), and actual crop evapotranspiration ($ET_{c\ act}$). One crucial element stood out during the review, which was in many cases the insufficient description of mulching characteristics in the experiments. Authors, reviewers, and editors should pay closer attention to this issue, as crucial details were identified to be missing in numerous publications.

Nevertheless, it was possible to draw conclusions regarding the beneficial effects of mulching in reducing soil evaporation and crop coefficients, particularly during the early stages of crop development. Among various mulching techniques, plastic film, and specifically black plastic, emerged as the most efficient. However, it was observed that the differences in the efficacy of mulching materials tended to be similar over the course of the season. Despite this, there is still considerable uncertainty associated with the effectiveness of black plastic mulching compared to other colors, as data often presents contradictions, which are likely due to insufficiencies in field observations and data reporting.

The existing guidelines for estimating the impacts of mulching on E_s, K_c, and $ET_{c\ act}$ during different crop stages were revised. These revisions were made by considering both the type of crop and the specific mulching material used. Unfortunately, in the case of organic mulching, incorporating the effect of residue rate into the guidelines remains challenging. Nevertheless, the guidelines provided in Tables 5 and 6 delineate the distinct effects of various mulching materials on crop evapotranspiration during different crop stages and should therefore be used as a reference for improving irrigation water management. However, it is crucial to refrain from saving water by surpassing the upper limits of the suggested ranges at the expense of inducing water stress in crops and compromising yields.

Acknowledgements This work was funded by national funds through FCT – Fundação para a Ciência e a Tecnologia, I.P., under projects UIDB/04129/2020 of LEAF-Linking Landscape, Environment, Agriculture and Food Research Unit; and UIDP/EEA/50009/2020 of LARSyS. The support of FCT through grants attributed to H. Darouich (https://doi.org/10.54499/CEECIND/01153/2017/CP1430/CT0002) and T.B. Ramos (https://doi.org/10.54499/CEECIND/01152/2017/CP1461/CT0019) is also acknowledged.

Author Contributions T.R. and H.D. performed the literature review; T.R. wrote the original draft of the paper. L.S.P. reviewed the paper and supervised all work.

Funding Open access funding provided by FCT|FCCN (b-on).

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

Acharya CL, Hati KM, Bandyopadhyay KK (2005) Mulches. In: Hillel D, Rosenzweig C, Pawlson DS, Sorger MI, Sparks DL, Hatfield J (eds) Encyclopedia of Soils, Elsevier, pp 521–532

Adams JE, Arkin GF, Ritchie JT (1976) Influence of row spacing and straw mulch on first stage drying. Soil Sci Soc Am J 40:436–442. https://doi.org/10.2136/sssaj1976.03615995004000030035x

Adil Rashid M, Zhang X, Andersen MN, Olesen JE (2019) Can mulching of maize straw complement deficit irrigation to improve water use efficiency and productivity of winter wheat in North China Plain? Agric Water Manage 213:1–11. https://doi.org/10.1016/j.agwat.2018.10.008

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration. Guidelines for Computing Crop Water requirements. FAO Irrig. Drain. Pap. 56. FAO, Rome, p 300

Allen RG, Walter IA, Elliot RL, Howell TA, Itenfisu D, Jensen ME, Snyder RL (2005a) The ASCE standardized reference evapotranspiration equation. Report 0-7844-0805-X, ASCE Task Committee on Standardization of Reference Evapotranspiration. American Soc. Civil Engineers, Reston, VA.

Allen RG, Pereira LS, Smith M, Raes D, Wright JL (2005b) FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions. J Irrig Drain Eng 131(1):2–13. https://doi.org/10.1061/(ASCE)0733-9437(2005)131:1(2)

Allen RG, Pereira LS, Howell TA, Jensen ME (2011) Evapotranspiration information reporting: I factors governing measurement accuracy. Agric Water Manage 98(6):899–920. https://doi.org/10.1016/j.agwat.2010.12.015

Ayas S (2023) Different irrigation and fertilization levels and mulching materials on the yield and quality of strawberry Ciência. Agrotec 47:e014122. https://doi.org/10.1590/1413-7054202347014122

Barros LCG, Hanks RJ (1993) Evapotranspiration and yield of beans as affected by mulch and irrigation. Agron J 85:692–697. https://doi.org/10.2134/agronj1993.00021962008500030032x

Basch G, Kassam A, González-Sánchez EJ, Streit B (2012) Making Sustainable Agriculture Real in CAP 2020: The Role of Conservation Agriculture. ECAF, Brussels (ISBN 978-84-615-8106-1), 43pp

Biswas T, Bandyopadhyay PK, Nandi R, Mukherjee S, Kundu A, Reddy P, Mandal B, Kumar P (2022) Impact of mulching and nutrients on soil water balance and actual evapotranspiration of irrigated winter cabbage (*Brassica oleracea* var capitata L). Agric Water Manage 263:107456. https://doi.org/10.1016/j.agwat.2022.107456

Blanco-Canqui H, Lal R (2007) Impacts of long-term wheat straw management on soil hydraulic properties under no-tillage. Soil Sci Soc Am J 71:1166–1173. https://doi.org/10.2136/sssaj2006.0411

Bond JJ, Willis WO (1969) Soil water evaporation: surface residue rate and placement effects. Soil Sci Soc Am J 33:445–448. https://doi.org/10.2136/sssaj1969.03615995003300030031x

Brar AS, Buttar GS, Thind HS, Singh KB (2019) Improvement of water productivity, economics and energetics of potato through straw mulching and irrigation scheduling in Indian Punjab. Potato Res 62:465–484. https://doi.org/10.1007/s11540-019-9423-6

Chai Y, Chai Q, Li R, Li Y, Yang C, Cheng H, Chang L, Chai S (2022) Straw strip mulching in a semiarid rainfed agroecosystem achieves winter wheat yields similar to those of full plastic mulching by optimizing the soil hydrothermal regime. Crop J 10:879–892. https://doi.org/10.1016/j.cj.2021.09.004

Chakraborty D, Nagarajan S, Aggarwal P, Gupta VK, Tomar RK, Garg RN, Sahoo RN, Sarkar A, Chopra UK, Sundara Sarma KS, Kalra N (2008) Effect of mulching on soil and plant water status, and the growth and yield of wheat (*Triticum aestivum* L.) in a semiarid environment. Agric Water Manage 95:1323–1334. https://doi.org/10.1016/j.agwat.2008.06.001

Chang L, Han F, Chai S, Cheng H, Yang D, Chen Y (2020) Straw strip mulching affects soil moisture and temperature for potato yield in semiarid regions. Agron J 112:1126–1139. https://doi.org/10.1002/agj2.20103

Chen Z, Sun S, Zhu Z, Jiang H, Zhang X (2019) Assessing the effects of plant density and plastic film mulch on maize evaporation and transpiration using dual crop coefficient approach. Agric Water Manage 225:105765. https://doi.org/10.1016/j.agwat.2019.105765

Cheng D, Wang Z, Yang L, Zhang L, Zhang Q (2021) Combined effects of mulching and crop density on soil evaporation, temperature, and water use efficiency of winter wheat. Exp Agric 57:163–174. https://doi.org/10.1017/S0014479721000119

Cook HF, Valdes GSB, Lee HC (2006) Mulch effects on rainfall interception, soil physical characteristics and temperature under Zea mays L. Soil till Res 91:227–235. https://doi.org/10.1016/j.still.2005.12.007

Eid TA, Abou Grah FII (2012) Effect of some mulching treatments on water use efficiency, yield and mineral composition of Le-Conte pear trees. Annals Agric Sci Moshtohor J 50:11–19

El-Naggar YI, Eid TA, Ali SAM (2018) Effects of mulching soil on water consumption, yield, fruit quality and water use efficiency of Canino apricot (*Prunus armeniaca* L.) cultivar. J Plant Prod Mansoura Univ 9(12):1003–1012. https://doi.org/10.21608/JPP.2018.36618

Feng Y, Hao W, Gao L, Li H, Gong D, Cui N (2019) Comparison of maize water consumption at different scales between mulched and non-mulched croplands. Agric Water Manag 216:315–324. https://doi.org/10.1016/j.agwat.2019.02.016

Ghawi I, Battikhi AM (1986) Watermelon (*Citrullus lanatus*) production under mulch and trickle irrigation in the Jordan Valley. J Agron Crop Sci 156:225–236. https://doi.org/10.1111/j.1439-037X.1986.tb00031.x

Gong D, Mei X, Hao W, Wang H, Caylor KK (2017) Comparison of ET partitioning and crop coefficients between partial plastic mulched and non-mulched maize fields. Agric Water Manag 181:23–34. https://doi.org/10.1016/j.agwat.2016.11.016

Guo H, Li S, Kang S, Du T, Tong L, Hao X, Ding R (2020) Crop coefficient for spring maize under plastic mulch based on 12-year eddy covariance observation in the arid region of Northwest China. J Hydrol 588:125108. https://doi.org/10.1016/j.jhydrol.2020.125108

Han S, Yang Y, Li H, Yang Y, Wang J, Cao J (2019) Determination of crop water use and coefficient in drip-irrigated cotton fields in arid regions. Field Crops Res 236:85–95. https://doi.org/10.1016/j.fcr.2019.03.008

Hassan AM, Magdy EA (2014) Effect of mulching and emitter spacing on water use efficiency and yield of squash. Misr J Agric Eng 31(3):897–918. https://doi.org/10.21608/MJAE.2014.98925

Igbadun HE, Oiganji E (2012) Crop coefficients and yield response factors for onion (*Allium cepa* L.) under deficit irrigation and mulch practices in Samaru, Nigeria. Afr J Agric Res 7(36):5137–5152. https://doi.org/10.5897/AJAR12.689

Jia Q, Shi H, Li R, Miao Q, Feng Y, Wang N, Li J (2021) Evaporation of maize crop under mulch film and soil covered drip irrigation: field assessment and modelling on West Liaohe Plain, China. Agric Water Manage 253:106894. https://doi.org/10.1016/j.agwat.2021.106894

Jovanovic N, Pereira LS, Paredes P, Pôças I, Cantore V, Todorovic M (2020) A review of strategies, methods and technologies to reduce non-beneficial consumptive water use on farms considering the FAO56 methods. Agric Water Manage 239:10626. https://doi.org/10.1016/j.agwat.2020.106267

Kahlon MS, Lal R, Ann-Varughese M (2013) Twenty two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. Soil till Res 126:151–158. https://doi.org/10.1016/j.still.2012.08.001

Karaer M, Gültaş HT, Kuşçu H (2023) The effects of plastic mulched drip irrigation on yield, fruit quality and water productivity of table tomatoes. Gesunde Pflanz 75:1591–1599. https://doi.org/10.1007/s10343-023-00848-x

Kasirajan S, Ngouajio M (2012) Polyethylene and biodegradable mulches for agricultural applications: a review. Agron Sustain Dev 32:501–529. https://doi.org/10.1007/s13593-011-0068-3

Kassam A, Basch G, Friedrich T, Shaxson F, Goddard T, Amado JCT, Crabtree B, Hongwen I, Mello I, Pisante M, Mkomwa S (2013) Sustainable soil management is more than what and how crops are grown. In: Lal R, Stewart BA (eds) Principles of sustainable Soil Management in Agroecosystems. Advances in Soil Science, pp 337–399

Klocke NL, Currie RS, Aiken RM (2009) Soil water evaporation and crop residues. Trans ASABE 52(1):103–110. https://doi.org/10.13031/2013.25951

Li FM, Wang P, Wang J, Xu JZ (2004) Effects of irrigation before sowing and plastic film mulching on yield and water uptake of spring wheat in semiarid Loess Plateau of China. Agric Water Manage 67:77–88. https://doi.org/10.1016/j.agwat.2004.02.001

Li SX, Wang ZH, Li SQ, Gao YJ, Tian XH (2013) Effect of plastic sheet mulch, wheat straw mulch, and maize growth on water loss by evaporation in dryland areas of China. Agric Water Manage 116:39–49. https://doi.org/10.1016/j.agwat.2012.10.004

Liao Y, Cao HX, Liu X, Li HT, Hu QY, Xue WK (2021) By increasing infiltration and reducing evaporation, mulching can improve the soil water environment and apple yield of orchards in semiarid areas. Agric Water Manage 253:106936. https://doi.org/10.1016/j.agwat.2021.106936

Lin W, Liu W, Zhou S, Liu C (2019) Influence of plastic film mulch on maize water use efficiency in the Loess Plateau of China. Agric Water Manage 224:105710. https://doi.org/10.1016/j.agwat.2019.105710

Liu M, Shi H, Paredes P, Ramos TB, Dai L, Feng Z, Pereira LS (2022a) Estimating and partitioning maize evapotranspiration as affected by salinity using weighing lysimeters and the SIMDualKc model. Agric Water Manage 261:107362. https://doi.org/10.1016/j.agwat.2021.107362

Liu M, Paredes P, Shi H, Ramos TB, Dou X, Dai L, Pereira LS (2022b) Impacts of a shallow saline water table on maize evapotranspiration and groundwater contribution using static water table lysimeters and the dual kc water balance model SIMDualKc. Agric Water Manage 273:107887. https://doi.org/10.1016/j.agwat.2022.107887

Lopez-Urrea R, Sanchez JM, Montoro A, Manas F, Intrigliolo DS (2020) Effect of using pruning waste as an organic mulching on a drip-irrigated vineyard evapotranspiration under a semi-arid climate. Agric Meteorol 291:108064. https://doi.org/10.1016/j.agrformet.2020.108064

Lu X, Li Z, Sun Z, Bu Q (2014) Straw mulching reduces maize yield, water, and nitrogen use in Northeastern China. Agron J 107:406–414. https://doi.org/10.2134/agronj14.0454

Montenegro AAA, Abrantes JRCB, de Lima JLMP, Singh VP, Santos TEM (2013) Impact of mulching on soil and water dynamics under intermittent simulated rainfall. CATENA 109:139–149. https://doi.org/10.1016/j.catena.2013.03.018

Mukherjee A, Kundu M, Sarkar S (2010) Role of irrigation and mulch on yield, evapotranspiration rate and water use pattern of tomato (*Lycopersicon esculentum* L). Agric Water Manage 98:182–189. https://doi.org/10.1016/j.agwat.2010.08.018

Odhiambo LO, Irmak S (2012) Evaluation of the impact of surface residue cover on single and dual crop coefficient for estimating soybean actual evapotranspiration. Agric Water Manage 104:221–234. https://doi.org/10.1016/j.agwat.2011.12.021

Olivier FC, Singels A (2012) The effect of crop residue layers on evapotranspiration, growth and yield of irrigated sugarcane. Water SA 38(1). https://doi.org/10.4314/wsa.v38i1.10

Patil A, Tiwari KN (2018) Evapotranspiration and crop coefficient of okra under subsurface drip with and without plastic mulch. Curr Sci 115(12). https://doi.org/10.18520/cs/v115/i12/2249-2258

Patra SK, Poddar R, Pramanik S, Bandopadhyay P, Gaber A, Hossain A (2023) Growth, yield, water productivity and economics of okra (*Abelmoschus esculentus* L.) in response to gravity drip irrigation under mulch and without-mulch conditions. Sci Hortic 321:113227. https://doi.org/10.1016/j.scienta.2023.112327

Pereira LS, Cordery I, Iacovides I (2009) Coping with Water Scarcity. Addressing the challenges. Springer, Dordrecht, The Netherlands, p 382

Pereira LS, Paredes P, Jovanovic (2020) Soil water balance models for determining crop water and irrigation scheduling focusing on the FAO56 method and the dual kc approach. Agric Water Manag 241:106357. https://doi.org/10.1016/j.agwat.2020.106357

Pereira LS, Paredes P, Hunsaker DJ, López-Urrea R, Mohammadi Shad Z (2021a) Standard single and basal crop coefficients for field crops. Updates and advances to the FAO56 crop water requirements method. Agric Water Manage 243:106466. https://doi.org/10.1016/j.agwat.2020.106466

Pereira LS, Paredes P, López-Urrea R, Hunsaker DJ, Mota M, Mohammadi Shad Z (2021b) Standard single and basal crop coefficients for vegetable crops, an update of FAO56 crop water requirements approach. Agric Water Manage 243:106196. https://doi.org/10.1016/j.agwat.2020.106196

Pereira LS, Paredes P, Espírito-Santo D, Salman M (2023a) Actual and standard crop coefficients for semi-natural and planted grasslands and grasses: a review aimed at supporting water management to improve production and ecosystem services. Irrig Sci. https://doi.org/10.1007/s00271-023-00867-6

Pereira LS, Paredes P, Oliveira CM, Montoya F, López-Urrea R, Salman M (2023b) Single and basal crop coefficients for estimation of water use of tree and vine woody crops with consideration of fraction of ground cover, height, and training system for Mediterranean and warm temperate fruit and leaf crops. Irrig Sci. https://doi.org/10.1007/s00271-023-00901-7

Petry MT, Magalhães TF, Paredes P, Martins JD, Ferrazza CM, Hünemeier GA, Pereira LS (2023) Water use and crop coefficients of soybean cultivars of diverse maturity groups and assessment of related water management strategies. Irrig Sci. https://doi.org/10.1007/s00271-023-00871-w

Petry MT, Tonetto F, Martins JD, Slim JE, Werle R, Gonçalves AF, Paredes P, Pereira LS (2024) Evapotranspiration and crop coefficients of sprinkler irrigated aerobic rice in southern Brazil using the SIMDualKc water balance model. Irri Sci. in press

Prajapati GV, Subbaiah R (2019) Crop coefficients of Bt. Cotton under variable moisture regimes and mulching. J Agrometeorol 21(2):166–170. https://doi.org/10.54386/jam.v21i2.227

Prosdocimi M, Tarolli P, Cerdà A (2016) Mulching practices for reducing soil water erosion: a review. Earth Sci Rev 161:191–203. https://doi.org/10.1016/j.earscirev.2016.08.006

Rallo G, Paço TA, Paredes P, Puig-Sirera A, Massai R, Provenzano G, Pereira LS (2021) Updated single and dual crop coefficients for tree and vine fruit crops. Agric Water Manage 250:106645. https://doi.org/10.1016/j.agwat.2020.106645

Ram H, Dadhwal V, Vashist KK, Kaur H (2013) Grain yield and water use efficiency of wheat (*Triticum aestivum* L.) in relation to irrigation levels and rice straw mulching in North West India. Agric Water Manage 128:92–101. https://doi.org/10.1016/j.agwat.2013.06.011

Rosa RD, Paredes P, Rodrigues GC, Alves I, Fernando RM, Pereira LS, Allen RG (2012) Implementing the dual crop coefficient approach in interactive software 1: background and computational strategy. Agric Water Manag 103:8–24. https://doi.org/10.1016/j.agwat.2011.10.013

Santosh DT, Mandal D, Tiwari KN (2021) Yield and quality response of turmeric (*Curcuma longa*) under drip irrigation and plastic mulch. Res Crops 22(4):959–967. https://doi.org/10.31830/2348-7542.2021.157

Sarkar S, Singh (2007) Interactive effect of tillage depth and mulch on soil temperature, productivity and water use pattern of rainfed barley (*Hordeum vulgare* L). Soil till Res 92:79–86. https://doi.org/10.1016/j.still.2006.01.014

Shanono NJ, Abba BS, Nasidi NM (2022) Evaluation of Aqua-Crop model using onion crop under deficit irrigation and mulch in semi-arid Nigeria. Turk J Agr Eng Res Turkager 3(1):131–145. https://doi.org/10.46592/turkager.1078082

Sharma NK, Singh PN, Tyagi PC, Mohan SC (1998) Effect of Leucaena mulch on soil-water use and wheat yield. Agric Water Manage 35:191–200. https://doi.org/10.1016/S0378-3774(97)00047-4

Shen Q, Ding R, Du T, Tong L, Li S (2019) Water use effectiveness is enhanced using film mulch through increasing transpiration and decreasing evapotranspiration. Water 11:1153. https://doi.org/10.3390/w11061153

Somanathan H, Sathasivam R, Sivaram S, Kumaresan SM, Muthuraman MS, Park SU (2022) An update on polyethylene and biodegradable plastic mulch films and their impact on the environment. Chemosphere 307:135839. https://doi.org/10.1016/j.chemosphere.2022.135839

Sun H, Shao L, Liu X, Miao W, Chen S, Zhang X (2012) Determination of water consumption and the water-saving potential of three mulching methods in a jujube orchard. Eur J Agron 43:87–95. https://doi.org/10.1016/j.eja.2012.05.007

Tian F, Yang P, Hu H, Dai C (2016) Partitioning of cotton field evapotranspiration under mulched drip irrigation based on a dual crop coefficient model. Water 8:72. https://doi.org/103390/w8030072

van Donk SJ, Martin DL, Irmak S, Melvin SR, Petersen JL, Davison DR (2010) Crop residue cover effects on evaporation, soil water content, and yield of deficit-irrigated corn in West-Central. Neb Trans ASABE 53(6):1787–1797. https://doi.org/10.13031/2013.35805

Vanuytrecht E, Raes D, Steduto P, Hsiao TC, Fereres E, Heng LK, Vila MG, Moreno PM (2014) AquaCrop: FAO's crop water productivity and yield assessment model. Environ Model Softw 62:351–360. https://doi.org/10.1016/j.envsoft.2014.08.005

Wang J, Zhang Y, Gong S, Xu D, Juan S, Zhao Y (2018) Evapotranspiration, crop coefficient and yield for drip-irrigated winter wheat with straw mulching in North China Plain. Field Crops Res 217:218–228. https://doi.org/10.1016/j.fcr.2017.05.010

Wang Z, Li M, Flury M, Schaeffer SM, Chang Ym Tao Z, Jia Z, Li S, Ding D, Wang J (2021) Agronomic performance of polyethylene and biodegradable plastic film mulches in a maize cropping system in a humid continental climate. Sci Total Environ 786:147460. https://doi.org/10.1016/j.scitotenv.2021.147460

Wang W, Li M, Wu J, Sun W, Ali S, Yang G, Pu Y, Liu L, Fang Y (2023) Cultivation practices with various mulching materials to regulate chlorophyll fluorescence, cuticular wax, and rapeseed productivity under semi-arid regions. Agric Water Manage 288:108465. https://doi.org/10.1016/j.agwat.2023.108465

Wen Y, Shang S, Yang J (2017) Optimization of irrigation scheduling for spring wheat with mulching and limited irrigation water in an arid climate. Agric Water Manage 192:33–44. https://doi.org/10.1016/j.agwat.2017.06.023

Yaghi T, Arslan A, Naoum F (2013) Cucumber (*Cucumis sativus* L.) water use efficiency (WUE) under plastic mulch and drip irrigation. Agric Water Manage 128:149–157. https://doi.org/10.1016/j.agwat.2013.06.002

Yan Q, Yang F, Dong F, Lu J, Li F, Duan Z, Zhang J, Lou G (2018) Yield loss compensation effect and water use efficiency of winter wheat under double-blank row mulching and limited irrigation in northern China. Field Crops Res 216:63–74. https://doi.org/10.1016/j.fcr.2017.11.009

Yang H, Wu G, Mo P, Chen S, Wang S, Xiao Y, Ma H, Wen T, Guo X, Fan G (2020) The combined effects of maize straw mulch and no-tillage on grain yield and water and nitrogen use efficiency of dry-land winter wheat (*Triticum aestivum* L). Soil till Res 197:104485. https://doi.org/10.1016/j.still.2019.104485

Zakari MD, Audu I, Igbadun HE, Nasidi NM, Ibrahim A, Shitu A (2019) Crop coefficient of tomato under deficit irrigation and mulch practices at Kano river irrigation project, Nigeria. Arid Zone J Eng Techn Enviro 15(4):823–836

Zayton AM, Guirguis AE, Allam KHA (2014) Effect of sprinkler irrigation management and straw mulch on yield, water consumption and crop coefficient of peanut in sandy soil Egypt. J Agric Res 92(2):657–672. https://doi.org/10.21608/EJAR.2014.155202

Zhang X, Pei D, Hu C (2003) Conserving groundwater for irrigation in the North China Plain. Irrig Sci 21:159–166. https://doi.org/10.1007/s00271-002-0059-x

Zhang QT, Ahmed OAB, Inoue M, Saxena MC, Inosako K, Kondo K (2009) Effects of mulching on evapotranspiration, yield and water use efficiency of Swiss chard (*Beta vulgaris* L. var. Flavescens) irrigated with diluted seawater. J Food Agric Environ 7(34):650–654

Zhang S, Li P, Yang X, Wang Z, Chen X (2011) Effects of tillage and plastic mulch on soil water, growth and yield of spring-sown

maize. Soil till Res 112:92–97. https://doi.org/10.1016/j.still.2010.11.006
Zhang M, Dong B, Qiao Y, Yang Y, Wang Y, Liu M (2018a) Effects of sub-soil plastic film mulch on soil water and salt content and water utilization by winter wheat under different soil salinities. Field Crops Res 225:130–140. https://doi.org/10.1016/j.fcr.2018.06.010
Zhang Y, Wang J, Gong S, Xu D, Sui J, Wu Z, Mo Y (2018b) Effects of film mulching on evapotranspiration, yield and water use efficiency of a maize field with drip irrigation in Northeastern China. Agric Water Manage 205:90–99. https://doi.org/10.1016/j.agwat.2018.04.029
Zheng J, Fan J, Zhang F, Yan S, Guo J, Chen D, Li Z (2018) Mulching mode and planting density affect canopy interception loss of rainfall and water use efficiency of dryland maize on the Loess Plateau of China. J Arid Land 10(5):794–808. https://doi.org/10.1007/s40333-018-0122-y