

Water footprint of globe artichoke: The impact of evaporative canopy-cooling irrigation

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ABSTRACT

Climate change and the increasing frequency of heatwaves represent major challenges for agriculture. Innovative cooling irrigation techniques can mitigate their adverse effects by enhancing growth rates and earliness, although often at the expense of a higher water consumption. This study assessed the agronomic impact of evaporative canopy-cooling irrigation management on globe artichoke (*Cynara cardunculus* L. var. *scolymus*) by using a water footprint approach to relate the actual water consumption to the yield. Field trials were carried out over three growing seasons of the cultivar “Spinoso sardo”, grown in the Mediterranean region of Sardinia (Italy) using a forcing cultivation technique. Canopy-cooling was applied using an automatic micro-sprinkler system when daily air temperature exceeded 25 °C and humidity fell below 70%. The canopy-cooling management reduced heat stress, decreasing head atrophy incidence by averagely 57% compared to the drip-irrigated control. Canopy-cooling did not affect the water footprint because the higher water consumption (+15%) was compensated by proportionally higher yields (+20%), with an average water footprint of 888 m³ t⁻¹. The blue water footprint weighted averagely 64% in both irrigation managements. The positive effects of canopy-cooling on yield were statistically significant only under severe heat stress, particularly during the inflorescence formation stage, leading to an increase of first-order heads. The water footprint analysis highlighted the importance of assessing the agronomic impact of irrigation by shifting from minimizing water use to maximising the yield per unit of water consumed, and of developing irrigation strategies to cope with climate change scenarios in Mediterranean horticultural agroecosystems.

1. Introduction

The greenhouse gas emissions of the anthropic activities have caused an increase of the median global temperature expected to rise up to 3.4 °C within 2100 (IPCC et al., 2023). The consequent global warming will lead to a growing intensity and frequency of extremely high temperature events with a severe impact on agriculture (Jiang et al., 2020). The heat stress affects growth, development and yield by influencing negatively the photosynthesis, sensitive to high temperature even before other cell functions (Long et al., 2006; Prasad et al., 2008). The high temperature implies an increase of the reference evapotranspiration, leading to a higher water consumption (Dono et al., 2013a, 2013b). In addition, it

causes an instantaneous heat stress during the hottest hours of the day (midday depression), characterised by a rise of the crop evapotranspiration, determining the closure of stomata, the consequent increase of the leaf temperature and the decline of the net photosynthetic rate (Hatfield and Dold, 2019; Mast and Yang, 2025). Indeed, temperature has a direct effect on photosynthesis by decreasing the carboxylation and electron transport in the photosystems (Akter and Rafiqul Islam, 2017). These combined effects are particularly critical in irrigated Mediterranean cropping systems, where the need for protecting the crops from heat stress may increase irrigation demand in regions already affected by limited water availability.

The problem of scarce water resources has traditionally been

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addressed by adopting drip irrigation, considered very efficient, but not able to prevent the stomatal closure during the midday depression, even in soils irrigated at field capacity, due to the heat stress caused to the leaves (Deligios et al., 2019; Gimenez et al., 2005). Furthermore, drip irrigation affects the root architecture and the soil water balance, concentrating the root growth in a smaller soil volume and closer to the surface, thus affecting negatively the water interception, absorption and productivity (Jha et al., 2017; Kaur et al., 2024). Drip irrigation is commonly adopted in Mediterranean irrigated crops such as artichoke (*Cynara cardunculus* subsp. *scolymus* L.), where the early flowering is achieved by applying the forcing technique to anticipate harvest and increase the income when the market price is higher (De Menna et al., 2018). The forcing technique requires abundant irrigation in summer to force the vegetative organs (shoots) to start growing instead of being dormant till the natural period of growth (Mameli et al., 2005; Pisanu et al., 2010). Artichoke is very sensitive to heat stress and the low water use efficiency of irrigation, especially during the early growth stages and the hottest hours of the day (Deligios et al., 2019). The temperature above 25 °C during the early flowering triggers the head atrophy, a physiopathy causing the bud malformation and necrotic areas in the central core cells, attributable to the excessive growth rate of the plant that does not allow some minerals (calcium and boron) to reach the shoot apex in differentiation (Magnifico et al., 1984).

Preventing or mitigating thermal stress and excessive heat is particularly important in open-field crops, where the possibility to influence the microclimate with irrigation is limited (Koscielny et al., 2018). Evaporative canopy-cooling (CC) has therefore been explored as a complementary irrigation strategy in orchards (Evans, 2004), vineyards (Caravia et al., 2017) and greenhouse crops (Leyva et al., 2015). The CC irrigation is conducted through micro-sprinklers that spray a mist above the canopy. The evaporation of the sprayed water absorbs sensible heat, thereby reducing leaf temperature, vapour pressure deficit and heat stress (Lazare et al., 2022). Evaporative CC irrigation can decrease the air temperature above the canopy by 1–3 °C, although its effectiveness depends on environmental conditions, particularly air temperature, relative humidity and evaporative demand (Liu et al., 2021). It is therefore expected to be more effective during severe hot and dry periods. However, canopy cooling requires additional water and should therefore be evaluated not only for its physiological and yield benefits, but also for its overall water use implications.

The water footprint (WF) approach provides a suitable framework for evaluating this trade off from both agronomic and environmental perspectives. In crop production, the WF quantifies the fresh water consumption and pollution in relation to the amount of product obtained, distinguishing between blue water from surface and ground-water resources, green water supplied by rainfall and stored in the soil, and grey water required to assimilate pollutant loads (Hoover et al., 2023). By expressing water use per unit of yield, the WF provides information that cannot be obtained by considering irrigation volumes alone. Indeed, an increase in absolute water consumption does not necessarily indicate a lower water use performance if it is accompanied by a proportional or greater increase in marketable yield. Consequently, the WF approach allows irrigation strategies to be assessed by considering freshwater use, crop productivity and water pollution together, rather than solely by minimizing the volume of water consumed.

Former experimental activities of the Authors were conducted on globe artichoke in a horticultural farm in Sardinia (Italy), which was infrastructured as a demonstrator of the Horizon 2020 project “Maslowaten”, focused on the study and dissemination of innovative irrigation managements based on photovoltaic pumping, precision and CC irrigation (<https://maslowaten.eu>, 2018). This project demonstrated the efficacy of CC in increasing yield and resilience to climate change of artichoke by mitigating the heat stress, with positive physiological effects on yield and earliness, in addition to reducing the head atrophy incidence (Deligios et al., 2019). However, the additional water required for CC was not evaluated through a WF approach, and it remained

unclear whether the associated yield increase was sufficient to compensate the higher water consumption. Therefore, the aim of the present study was to conduct a WF analysis on a three-year cultivation of intensive globe artichoke adopting an integrated CC irrigation management based on sprinkler irrigation and evaporative CC, to evaluate its sustainability on the water use compared to conventional drip irrigation. The results aimed to determine whether the improvements in crop performance achieved with CC are sufficient to offset the additional water use expressed per unit of marketable yield.

2. Materials and methods

2.1. Artichoke experimental field

The evaluation of the water footprint was conducted on three artichoke crop cycles during the 2018–2021 seasons in a horticultural farm located in Uri (Sardinia, Italy, 40°37'25" N, 8°28'16" E, 128 m asl). The soil had a clay-loam texture, with a water retention capacity between 25% and 28% when measured on a dry basis. This region had typical Mediterranean climate conditions characterised by mild temperature and average annual humidity of 65%. The average yearly rainfall was 675 mm, primarily occurring in autumn, while the average temperature ranged from 8.2 °C in February to 30.3 °C in August. Meteorological data were collected from the weather station located in the farm and from the Agrometeorological Service of the Sardinia Region, Italy (ARPA, 2025).

Globe artichoke (*Cynara cardunculus* subsp. *scolymus* L.) of Spinoso sardo varietal type was cultivated with a plant density of 11700 plants ha⁻¹ (1.5 m row width and 0.57 m row spacing) on a total area of 0.5 ha. The conventional forcing technique was employed. The soil was prepared with plowing and harrowing. Planting was carried out in late June using semi-dormant ovuli, about 10 cm in length each. Pest and disease management, along with fertilization, followed the farmer's ordinary practices. The total amount of fertilizer was 150, 80 and 100 kg ha⁻¹ for N, P and K, respectively, distributed in three applications during planting, mid-September and late November. Weeds were managed through mechanical methods.

2.2. Irrigation managements

The experimental area was divided into two plots with an area of 0.25 ha each, characterised by two irrigation managements: conventional (CV) and canopy-cooling (CC). Both plots (sectors) were located in an area of the farm with homogenous soil and climate conditions measured by the weather station located in the middle. The use of two large management sectors was dictated by the operational constraints of the farm-scale irrigation infrastructure. The establishment of multiple small randomised plots was not technically feasible because the cooling mist could drift into neighbouring plots, causing treatment interference, and because the system relied on a centralised irrigation network, soil moisture sensors, weather station and automated control unit operating at sector scale. This configuration reflects the practical constraints commonly encountered in experiments conducted under commercial farm conditions, as discussed by Gomez and Gomez, (1984). Consequently, the irrigation treatments were not spatially replicated.

The irrigation of the CV management (used as control area) was applied using a drip system with drippers spaced 1.50 × 0.35 m and a flow rate of 2.3 L h⁻¹. Drip irrigation was provided from planting to mid-October, thus till the first effective rainfall events, according to the farmer experience and without any technological or decision support. In the CC management area, both irrigation and evaporative CC were performed by an integrated precision micro-sprinkler irrigation system with sprinklers spaced 5.0 × 4.5 m mounted 1.0 m above ground (Rivulis Aquamaster 2005, Israel), capable to work alternatively in sprinkler or CC irrigation mode. In sprinkler irrigation mode (flow rate of 70 L h⁻¹ and sprinkler pressure of 2.0 bar), the system was managed

automatically through precision irrigation technologies characterised by a wireless control unit that communicated with an integrated weather station and soil moisture sensors installed at 10, 20 and 30 cm depth. The control unit activated the sprinkler irrigation when the soil moisture at 10 cm was below 35% of the available water and stopped when the soil moisture was 70% at 30 cm to prevent deep percolation. When operating in CC mode (flow rate of 61 L h⁻¹ and sprinkler pressure of 1.5 bar), the micro-sprinklers produced a mist over the canopy when the hourly day-time temperature from 11:00–17:00 (6 h day⁻¹) was over 25 °C and air humidity under 70% (Fig. 1). Each cooling event had a duration of 15 min and was repeated after 45 min only when the heat stress persisted to allow the complete water evaporation from the canopy. The CC started 45 days after planting (around mid-August) and was supplied for 60 days (till mid-October) during the critical phenological stage of the cauline apex differentiation from vegetative to reproductive growth (Farris et al., 2024). The water use efficiency (WUE) of both irrigation managements was calculated with the ratio between the fresh yield and the total water consumption.

The irrigation of CC was provided in the same period of the CV management. The heat stress was measured using both the heat hours and the stress degree days (SDD). The heat hours are defined as the number of hours during which the air temperature exceeded the optimal temperature of artichoke (25 °C for Spinoso sardo varietal type), corresponding to the hours of operation of CC irrigation mitigating the heat stress. The SDD were calculated as the difference between the maximum daily temperature and the optimal temperature of the crop (MRCC, 2013), that was 25 °C for artichoke.

2.3. Artichoke yield and statistical analysis

The experiment was organised as a farm-scale comparison of two irrigation management strategies conducted over three consecutive growing seasons. Within each irrigation sector, plants were used as sampling units for the assessment of yield and head traits; they did not represent independent field replicates of the irrigation treatments.

The marketable artichoke heads were harvested weekly from December to February and sorted by order (I, II and III) from 18 sample plants in each irrigation management sector. The crop cycles were dismissed in March. The percentage of atrophic heads was measured on 24 sampled plants per irrigation management sector. Data was checked for normality prior to elaboration. Statistical differences and comparisons of the total yield, irrigation volumes and WF between irrigation

managements and crop cycles were analysed with analysis of variance ($p < 0.05$) and LSD test ($p < 0.05$).

2.4. Water footprint methodology

The WF was considered the sum of three components, calculated in m³ t⁻¹ of fresh artichoke heads:

$$WF = WF_{blue} + WF_{green} + WF_{grey} (\text{m}^3 \text{t}^{-1}) \quad (1)$$

where WF_{blue} , WF_{green} and WF_{grey} are the blue water, green water and grey water footprints, respectively. Blue water, originating from surface and groundwater sources, is crucial for irrigated crops and comprises the surface water from rivers, lakes, reservoirs or groundwater used for irrigation (Hoekstra and Mekonnen, 2012), while green water, deriving from rainfall and accumulated in the soil, primarily supports rainfed crops, which rely on natural precipitation patterns (Rockström et al., 2009). The third component of the WF is the grey water, that is the water required for diluting the critical contaminants deriving from the agricultural activity, mainly nitrogen fertilizers (Muratoglu, 2020). The main pollutants released during a crop cycle are nitrates due to use of nitrogen fertilizers, that pose a significant risk of environmental contamination of soil and surrounding water bodies, with negative effects also on human health (Chapagain et al., 2006; Li et al., 2024). Indeed, nitrate is the most mobile, widespread contaminant due to intensive fertilization, directly linked to water quality standards (Hu et al., 2018; Olivera Rodriguez et al., 2021). Other contaminants such as phosphorus, pesticides or other chemicals are not usually included in grey water footprints because their diffused pollution present methodological challenges including data scarcity, temporal-spatial variability and interaction effects that leads to difficulties in modelling their diffusion and deep leaching (Doğan and Capar, 2026).

2.4.1. Blue water footprint

The WF_{blue} was calculated separately for CV and CC managements, with drip irrigation (WF_{blueCV}) and micro-sprinkler system (WF_{blueCC}), respectively. The WF_{blueCV} was calculated as the sum of the metered amount of irrigation water supplied during the irrigation season (IW_{CV}) from planting day (d_i) to mid-October, corresponding to an irrigation season around 108 days after planting (d_e), divided by the observed yield:



Fig. 1. Micro-sprinkler irrigation system operating in canopy-cooling mode on the artichoke experimental field.

$$WF_{blueCV} = \sum_{d_i}^{d_e} IW_{CV} / Y_{CV} (\text{m}^3 \text{t}^{-1}) \quad (2)$$

in which Y_C is the fresh head yield of the CV sector in t ha^{-1} calculated at the end of the crop cycle. The IW_{CV} was based on the time duration of the daily irrigation measured during the experimental crop cycles with the equation:

$$IW_{CV} = \sum_{d_i}^{d_e} (w_d n_d t_d) / A (\text{m}^3 \text{ha}^{-1}) \quad (3)$$

where w_d is the flow rate of the drippers in $\text{m}^3 \text{h}^{-1}$, n_d the number of drippers of the control sector, t_d the metered time duration of the daily irrigation in h and A the irrigated area of CV. The WF_{blue} of CC (WF_{blueCC}) was calculated using the IW_{CC} , that was the sum of the sprinkler irrigation water supplied from planting day d_i to around the middle of October d_e (IW_{CCS}) and the water supplied for canopy-cooling (IW_{CCI}):

$$IW_{CC} = \sum_{d_i}^{d_e} (IW_{CCS} + IW_{CCI}) (\text{m}^3 \text{ha}^{-1}) \quad (4)$$

Accordingly, the WF_{blueCC} is equal to:

$$WF_{blueCC} = \sum_{d_i}^{d_e} IW_{CC} / Y_{CC} (\text{m}^3 \text{t}^{-1}) \quad (5)$$

where Y_{CC} is the total fresh head yield of CC at the end of the crop cycle in t ha^{-1} . The IW_{CC} of the mini-sprinkler system was calculated as following:

$$IW_{CC} = \sum_{d_i}^{d_e} (w_s n_s t_s) / A (\text{m}^3 \text{ha}^{-1}) \quad (6)$$

being w_s , n_s and t_s the flow rate, number and the metered time duration of the irrigation with the micro-sprinklers. Similarly, the IW_{CCI} was calculated as:

$$IW_{CCI} = \sum_{d_{ic}}^{d_{ec}} (w_{cc} n_s t_{cc}) / A (\text{m}^3 \text{ha}^{-1}) \quad (7)$$

where w_{cc} and t_{cc} indicated the flow rate and metered daily time duration of the micro-sprinklers during the mist irrigation, with d_{ic} and d_{ec} the first (day 45) and last day (day 105) of CC.

2.4.2. Green water footprint

The WF_{green} was calculated as the daily minimum value between the effective rainfall (P_{eff}) occurred during the crop cycle and the daily crop evapotranspiration rate (ET_c) (Li et al., 2024):

$$WF_{green} = \left(\sum_{d_i}^{d_e} \min(P_{eff}, ET_c) \cdot 10 \right) / Y_{CC} (\text{m}^3 \text{t}^{-1}) \quad (8)$$

The P_{eff} was estimated based on the monthly rainfall P of the each month (m) till the final month (e) of the cycle, according to the empiric formula of the CROPWAT model, also called Smith method (Smith and FAO, 1992):

$$P_{eff} = \sum_{m=1}^{m=e} \begin{cases} \frac{P(125 - 0.2P)}{125} & \text{for } P \leq 250 \text{ mm} \\ 125 + 0.1P & \text{for } P > 250 \text{ mm} \end{cases} (\text{mm}) \quad (9)$$

The ET_c was calculated as following:

$$ET_c = ET_0 K_c (\text{mm}) \quad (10)$$

where ET_0 was the reference crop evapotranspiration rate and K_c the crop coefficient of globe artichoke *Spinoso sardo* varietal type, ranging

from 0.3 to 0.9 depending on the month (Soddu et al., 2004). The ET_0 was calculated with the Hargreaves equation (Hargreaves and Samani, 1985):

$$ET_0 = 0.0023 R_a (T + 17.8) \Delta T^{0.5} (\text{mm}) \quad (11)$$

where R_a was the extraterrestrial radiation in MJ m^{-2} , retrieved from the NASA online georeferenced database (NASA, 2024) for the location and period of interest, T the average daily temperature and ΔT the daily thermal excursion, calculated as the average of the mean maximum minus minimum daily temperature.

2.4.3. Grey water footprint

The WF_{grey} derived from nitrogen pollutants was calculated as the ratio between the yearly nitrogen leaching and the difference between the maximum acceptable level of nitrogen concentration in water bodies (C_{max}) and its natural concentration in the water bodies (C_{nat}) in the pristine state (Mekonnen and Hoekstra, 2015; Rodríguez et al., 2024):

$$WF_{grey} = [L / (C_{max} - C_{nat})] / (Y_{CV} \text{ or } Y_{CC}) (\text{m}^3 \text{t}^{-1}) \quad (12)$$

where L was the nitrogen leaching retrieved from the nitrogen balance, C_{max} was considered according to the Italian standard of nitrate concentration for safe human water consumption, equal to 50 mg L^{-1} (Decree Dlgs 31, 2001), corresponding to 11.3 mg L^{-1} of nitrogen, whereas C_{nat} was assumed 0 mg L^{-1} , since the initial soil concentration of nitrogen before the artichoke cycles was unknown. The calculation of L followed and modified the approach based on the nitrogen balance (Olivera Rodríguez et al., 2021):

$$L = [N_i + AR + N_{min} + A_{Dep} - (U + V)] \beta (\text{kg ha}^{-1}) \quad (13)$$

where N_i is the initial nitrogen concentration in the soil before sowing (assumed 0 because it was not known), AR the nitrogen fertilizer application rate (150 kg N ha^{-1} per cycle), N_{min} the nitrogen mineralization rate, V the nitrogen volatilization rate, A_{Dep} the atmospheric nitrogen deposition (2.4 kg ha^{-1} per cycle) calculated from (Markaki et al., 2010), U the nitrogen uptake of the yield and β is a leaching fraction coefficient. According to the experimental data of Zhang et al., (2015), V was assumed equal to 4% of AR (6.0 kg ha^{-1} per cycle) and N_{min} was estimated 2.1 kg ha^{-1} per cycle, using the following empiric formula:

$$N_{min} = 1.5908 e^{0.002 AR} (\text{kg ha}^{-1}) \quad (14)$$

The nitrogen uptake U was calculated multiplying the yield by the average N content of the artichoke heads, measured by dry combustion in an elemental analyser LECO 628 (628 Series; LECO Corp., St. Joseph, MI, USA). The coefficient β was estimated using the guidelines and the equation proposed by Franke et al., (2013):

$$\beta = \beta_{min} + \left[\sum S_i (W_i / \sum W_i) \right] (\beta_{max} - \beta_{min}) (\text{dimensionless}) \quad (15)$$

where β_{max} and β_{min} represented the maximum and minimum leaching-runoff fraction, respectively, S_i the leaching-runoff score per factor affecting the leaching and W_i the weight of the factor attributable from the nitrogen table of factors (Franke et al., 2013).

3. Results

3.1. Meteorological data and yield results

The meteorological trend during the three crop cycles is depicted in Fig. 2. The hottest and driest summer was observed in 2019 (cycle 2), with an average daily temperature of 27.1°C during the June-September period (maximum temperature up to 38°C), with the lowest effective rainfall P_{eff} of 40 mm , followed by the 2020 summer of Cycle 3 (average temperature of 25.1°C and P_{eff} of 44 mm). Cycle 1 was the mildest, with

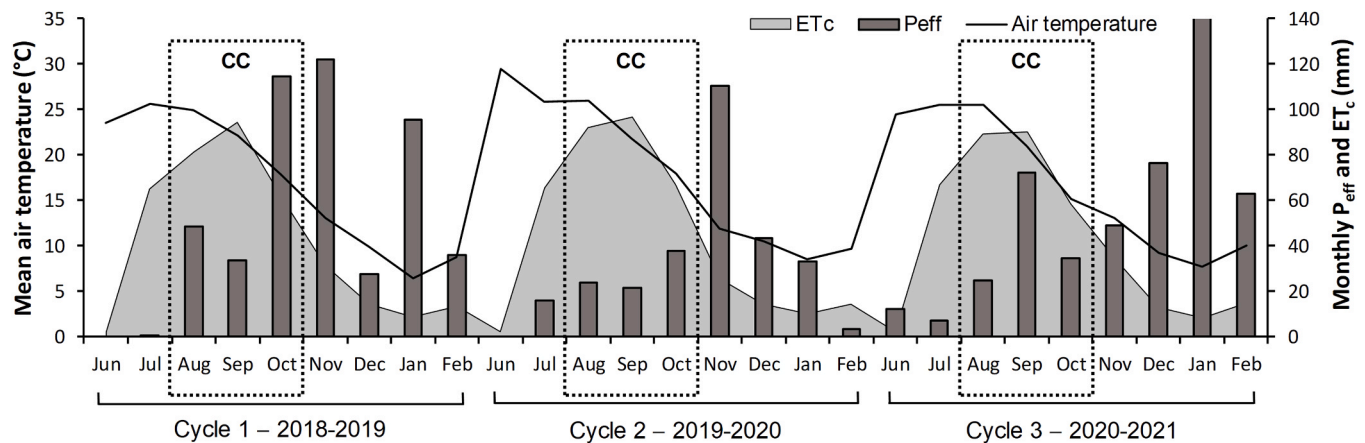


Fig. 2. Climate data over the three crop cycles till last harvest in February. Average air temperature (T), monthly effective precipitation (P_{eff}) and evapotranspiration rate (ET_c) are depicted. The canopy-cooling (CC) period is highlighted with a dotted area.

24.7 °C and the highest P_{eff} of 49 mm. During the CC period (from mid-August to mid-October), the cumulated P_{eff} was 197, 83 and 108 mm for cycle 1, 2 and 3, respectively. The monthly ET_c started raising from transplantation at the end of June and remained sustained till September (82 mm as the average of the three cycles), with the highest value of 97 mm reached in September 2019. The heat stress hours, corresponding to the hours of operation of CC irrigation, reached the highest value in cycle 2 (63 h), with a maximum temperature of 39.3 °C in August, followed by Cycle 3 with 50 h (Fig. 3).

The fresh yield of CC was 20% higher (9.8 t ha⁻¹) than CV (8.2 t ha⁻¹), as the average of the three cycles (Table 1). While no statistical yield differences between irrigation managements were observed in cycle 1 (around 5%), significant effects occurred in cycle 2 and 3, which suffered the most extreme summer temperature, where CC resulted 32% and 29% more productive than CV, respectively. Significant differences on the head dry matter and average head fresh weight were observed only in cycle 3 and the total head number per hectare did not differ between managements and cycles.

The head partitioning was distributed differently among orders: the I order heads represented between 15% and 24% of the total in the CC management and were 118% and 46% higher than CV in cycle 2 and 3, respectively. In Cycle 2 the II order heads in the CC were 48% higher than CV which, on the other hand, showed III order heads 77% higher than CC. The CC contributed to a significant reduction of head atrophy in all crop cycles by 57% on average. The average WUE calculated on the fresh yield (1.96 kg m⁻³) resulted different between years but not

between irrigation managements, reaching the highest and the lowest values in cycle 1 (2.30 kg m⁻³ as the average of both managements) and cycle 2 (1.70 kg m⁻³), respectively.

The yield reduction and head atrophy incidence of the two irrigation managements increased more than proportional to the increase of heat stress, determining growing and remarkable yield losses (Fig. 4). The CV suffered a yield reduction of 0.54% for each additional SDD, whereas the CC showed a lower reduction of 0.18%. Cycle 1 was subjected to a moderate heat stress of 103 SDD during the operating period of CC irrigation, since the average incidence of head atrophy of CV (8.8%) did not lead to a significant yield loss compared to CC. Conversely, cycles 2 and 3 accumulated 139 and 155 SDD, respectively, which significantly reduced the yield with a head atrophy of 20–25% in the CV management. As a result, it can be deduced that a heat stress around 135 SDD can be considered a thermal threshold for severe heat stress on artichoke from mid-August to mid-October, which was a critical period for inflorescence formation and growth.

The 20% increase in average yield was associated to a 15% higher average water consumption, equal to 5050 m³ ha⁻¹ for CC and 4400 m³ ha⁻¹ for the CV management, respectively (Fig. 5). The highest difference was observed after cycle 2 (20%) while the lowest after cycle 1 (11%). The average incidence of CC on the total water consumption was 28% (up to 31% in cycle 2), resulting in an average consumption of 3600 m³ ha⁻¹ of the sprinkler irrigation in the CC management, that was 17% less than drip irrigation of the CV management.

3.2. Globe artichoke water footprint

The WF analysis showed no statistical differences between irrigation managements with an average of 888 and 988 m³ t⁻¹ in CC and CV management, respectively (Fig. 6). The maximum WF was observed in CV after cycle 3, with 1144 m³ t⁻¹, whereas the minimum after cycle 1, with 770 m³ t⁻¹. The WF_{blue} had the highest impact on the total WF, equal to 64% (up to 70% in cycle 2 of the CC management), followed by WF_{green} (25%) and WF_{grey} (12%), as the average of both irrigation managements. The ratio WF_{blue} / WF_{green} ranged between 2.15 in cycle 1 and 3.08 in cycle 2 for the CV management, and from 2.43 to 3.69 in the CC management, that was between 13% and 18% higher. The WF_{grey} was calculated based on the average N content of the artichoke heads of 2.1%, resulting from the laboratory analysis.

4. Discussions

4.1. Agronomic and physiological benefits of canopy-cooling irrigation

The ET_c of artichoke grown using the forcing technique was

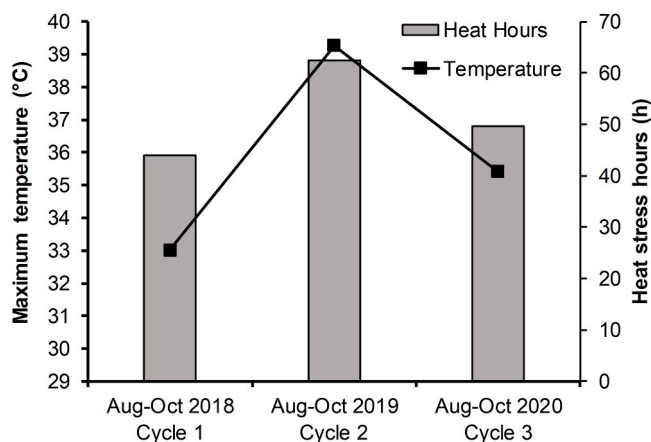


Fig. 3. Maximum temperature and heat stress hours from mid-August to mid-October of the three crop cycles.

Table 1

Globe artichoke yield and head characteristics under conventional and canopy-cooling irrigation management during the three crop cycles. Values are reported as mean $\pm$ standard deviation. The percentage distribution of heads among first-, second-, and third-order heads and water-use efficiency (WUE) are also reported. Results of the analysis of variance for irrigation treatment, year, and their interaction are shown at the bottom of the table. Means of the same parameter that do not share a letter are significantly different according to the post hoc test ($p < 0.05$).

Irrigation treatment	Fresh Yield (t ha ⁻¹)	Dry matter (%)	Head fresh weight (g)	Head atrophy (%)	Heads ha ⁻¹	Head distribution by order (%)			WUE (kg m ⁻³)
						I	II	III	
<i>Cycle 1–2018–2019</i>									
Canopy-cooling	10.5 ± 2.1 a	14.9 ± 0.02 a	152 ± 9 ab	0.0 ± 0.0 a	72775 ± 29358 ab	15 a	45 d	44 d	2.19 ± 0.87 a
Conventional	10.0 ± 1.3 a	15.0 ± 0.01 a	144 ± 14 ab	8.3 ± 0.4 b	74075 ± 19653 ab	13 a	42 d	39 d	2.41 ± 0.65 ab
<i>Cycle 2–2019–2020</i>									
Canopy-cooling	9.7 ± 1.8 a	16.1 ± 0.02 b	154 ± 12 b	12.5 ± 0.6c	67577 ± 22890 a	24 b	40 a	35c	1.80 ± 0.66 bc
Conventional	7.4 ± 1.1 bc	16.2 ± 0.02 b	143 ± 14 ab	25.0 ± 1.1 d	55231 ± 13784 ab	11 a	27 b	62 e	1.61 ± 0.46c
<i>Cycle 3–2020–2021</i>									
Canopy-cooling	9.2 ± 2.0 ab	22.2 ± 0.02c	163 ±10c	16.7 ± 0.8c	55880 ± 16809 ab	22 b	43 d	35c	1.89 ± 0.60 bc
Conventional	7.2 ± 1.3c	19.6 ± 0.03 d	149 ± 18 a	20.8 ± 1.0 e	48084 ± 17435 b	15 a	52 d	43c	1.67 ± 0.62 c
<i>Analysis of variance</i>									
Treatment	**	**	***	***	n.s.		n.s.		n.s.
Year	*	***	*	***	***		n.s.		***
Treatment × Year	n.s.	***	n.s.	***	n.s.		n.s.		n.s.

Significance: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; n.s.: not significant difference

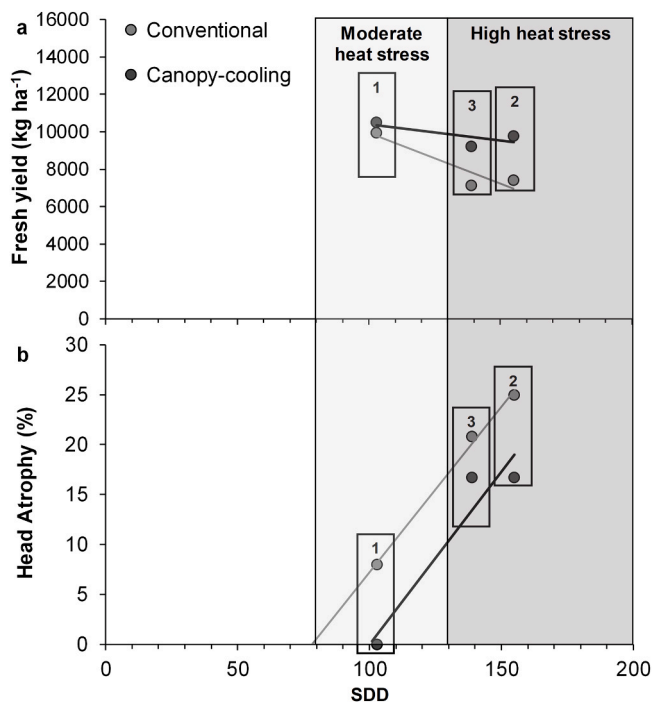


Fig. 4. Relation between fresh yield and SDD from mid-August to mid-October (a): conventional drip irrigation ($-54.05x + 15338$, $R^2 = 0.86$) and canopy-cooling irrigation management ($-17.63x + 12179$, $R^2 = 0.55$). Relation between head atrophy and SDD (b): conventional ($0.3318x - 25.97$, $R^2 = 0.99$) and canopy-cooling ($0.3435x - 34.56$, $R^2 = 0.93$). The rectangles group data of the same cycle.

considerable both at the beginning and the end of the crop cycle (Fig. 2). While cycle 1 had a relatively mild summer, the significant heat stress hours observed in cycle 2 and 3 (Fig. 3) highlighted the role of CC irrigation in limiting the atrophy of the flower buds by 57% on average compared to CV, resulting in more I order heads, which are the most profitable for the farmer, with a consequent higher yield (Table 1). Indeed, the reduction of leaf temperature and transpiration can reduce

the calcium-related disorders and possibly mitigate the head atrophy (Cantore et al., 2016). Beside the reduction of head atrophy, this result suggests that the stress mitigation of CC may have increased the head earliness, as already observed on artichoke, together with an increase of plantlets establishment (Mauro et al., 2008). On the other hand, the CV management in Cycle 2 and 3 showed that the crop subjected to exceptional heat stress (less I order heads) can partly recover the phenological delay by increasing the percentage of III order heads, which possibly explains the slight differences of the average fresh and dry weight and the absence of significant differences on the total number of heads between irrigation managements. The average increase of water consumption of 15% with the CC irrigation was compensated by a more than proportional increase of the yield by 20%. The WUE was not significantly affected by CC irrigation, but it differed between cycles. Indeed, the WUE was strictly dependent on the heat stress hours, showing the highest value after cycle 1, with the mildest summer. On the contrary, the lowest WUE of cycle 2 and 3 was due to the combination of high temperature and low humidity, which is known to damage the crop and decrease WUE and crop productivity (Fenner et al., 2019; Hatfield and Dold, 2019).

The heat stress reduced the artichoke production on CV (0.54% SDD⁻¹) more than proportional to CC (0.18% SDD⁻¹), with no significant reduction in cycle 1, where the heat stress was moderate (Fig. 4). The positive effect of CC irrigation was observed during the hottest and driest summer of cycle 2 and 3 (daily average temperature of 26–27 °C in summer and maximum temperature of 39 °C), when more than 135 SDD were cumulated during the daytime period of CC operation. Since an average temperature above 25 °C is considered a threshold that can trigger inflorescence abortion (Bianco and Calabrese, 2009), the CC irrigation can be considered effective on artichoke only in case of extreme temperatures in summer, where the cooling effect can mitigate the heat stress during the critical phenological stage of inflorescence formation. Earlier varieties less susceptible to head atrophy such as Tema 2000 (Farris et al., 2024), or postponing planting after the extreme temperature periods can be considered strategies of resilience to heat stress of intensive artichoke cropping systems.

4.2. Impact of artichoke water footprint

The higher water consumption of CC led to a negligible impact on the

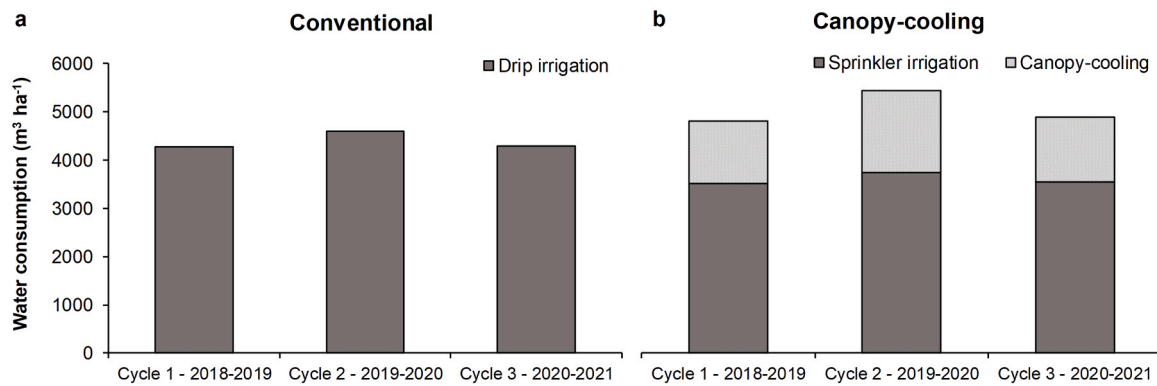


Fig. 5. Water consumption of conventional drip irrigation (a) and canopy-cooling management with sprinkler irrigation and additional evaporative canopy-cooling (b).

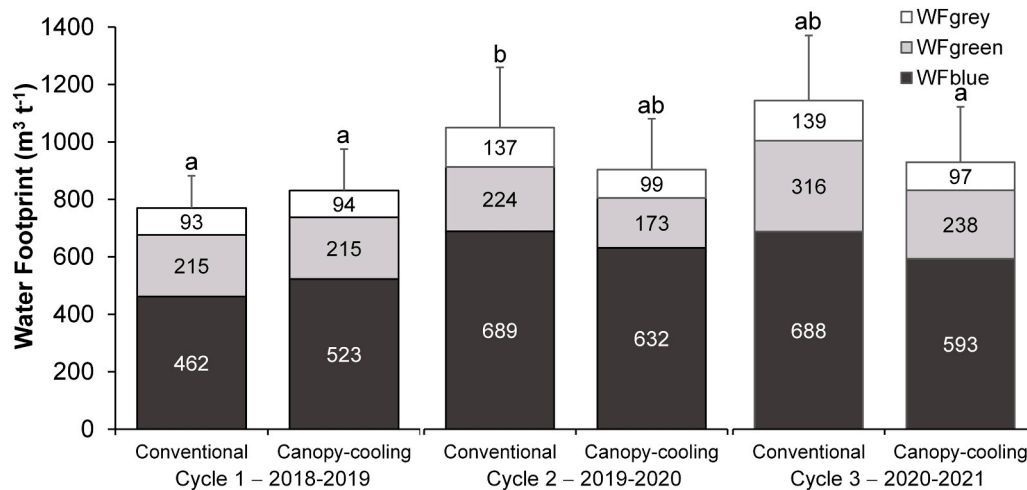


Fig. 6. Artichoke water footprint and standard deviation on the three crop cycles, divided into blue, green and grey water footprint. Results of the analysis of variance ($p < 0.05$): management (n.s.); year (n.s.), management $\times$ year (n.s.). Means that do not share a letter are significantly different (LSD test, $p < 0.05$).

artichoke WF compared to CV (Fig. 6). The average WF of $888 \text{ m}^3 \text{t}^{-1}$ was essentially in agreement (8% higher) with what calculated by former studies on artichoke, where it was estimated $818 \text{ m}^3 \text{t}^{-1}$ with a lower incidence of the WF_{blue} (29% instead of 62%) due to use of conventional irrigation only (Sarma et al., 2019). This difference can be considered very limited, since the approximation in estimating the WF of the crops can reach $\pm 30\%$ due to the uncertainty of the input data (Zhuo et al., 2014). The fluctuations of WF between crop cycles underlines the importance of long-term experiments to improve the data accuracy and assess reliably the water consumption of cropping systems in relation to the climate conditions. The higher water consumption of CC was counterbalanced by the higher yield, resulting in no significant effect on the average WF. Accordingly, the environmental sustainability and effectiveness of the CC technique is demonstrated when the water consumption is related to the unit of fresh product rather than unit of field area, providing a more objective estimation of the impact on water consumption.

The results of cycle 1, characterised by no yield difference between irrigation managements, indicated that mild summers with sufficient rainfall nullify the efficacy of CC, resulting in a higher water use without a substantial increase of yield. Therefore, forecasting potential extreme temperature periods is important to protect the crop from heat stress effectively without wasting water resource. The CV management resulted in a WF_{blue} between two and three times higher than WF_{green} and this proportion was 13–18% higher in the CC management. This is important to determine the sustainability of water use in terms of water

saving potential and increase of yield, according to the actual water availability (Duan et al., 2024). Numerical weather prediction models and alert systems in agriculture have improved their accuracy in predicting heatwaves or cold snaps (Bal et al., 2025) and can be used to assess whether to apply CC for mitigating the heat stress. The water use was more efficient in the CC irrigation management due to automatic irrigation technologies operating with air temperature thresholds. The average water consumption of CV ($4400 \text{ m}^3 \text{ha}^{-1}$) was 10% higher than the water volume commonly required in Mediterranean artichoke cropping systems of $4000 \text{ m}^3 \text{ha}^{-1}$ (Tesi, 2010), indicating a sub-optimal management of drip irrigation, whereas the sprinkler irrigation of CC amounted to $3600 \text{ m}^3 \text{ha}^{-1}$ (Fig. 5).

4.3. Limitations of the water footprint assessment on canopy-cooling irrigation

The calculation of the WF of the irrigation managements was conducted according to some limitations and assumptions, due to the specific features of CC. The first limitation concerned the farm-scale experimental layout. The two irrigation management strategies were applied to two large sectors without spatial replication because the centralised irrigation infrastructure and the risk of interference from cooling mist among adjacent plots prevented the establishment of multiple randomised treatment plots. However, the comparison was conducted over three consecutive growing seasons characterised by contrasting thermal and rainfall conditions, allowing the temporal

consistency of the observed responses to be assessed. In addition, the comparison involved two integrated management strategies: conventional farmer-operated drip irrigation and sensor-based micro-sprinkler irrigation combined with evaporative CC. Therefore, the effects of CC management may be due to a combined role of evaporative cooling and precision irrigation. In addition, the absence of independent field-level replication due to the experimental setup constraints inside the commercial farm represented a limitation of the experimental design and restricts the extent to which the analysis of variance results can be generalized beyond the experimental site. Consequently, the results should be interpreted as evidence of treatment-associated differences under the specific experimental conditions investigated, rather than as definitive evidence applicable to all field conditions.

A second limitation involved the estimation of WF_{blue} , which was calculated as the total volume of irrigation water applied, without separating the fractions lost through deep percolation and runoff, that can be commonly incorporated through the calculation of the water balance or by applying irrigation efficiency coefficients (Borsato et al., 2019; Gebremariam et al., 2021). This simplification was adopted because a physically based partition of applied water would have required detailed technical information on the micro-sprinkler irrigation-system performance both in irrigation and CC mode, which were not available in the present experiment. Indeed, the metered water applied with micro-sprinkler irrigation did not translate directly into crop use: canopy interception, airborne evaporation, soil wetting, throughfall, dripping, and stemflow all alter the fate of applied water, and these components change with canopy development, nozzle characteristics, and irrigation timing (Li, 2018; Salvador et al., 2023). Under these conditions, it was not possible to quantify the proportion of sprayed water effectively intercepted by the canopy and contributing to crop cooling, as distinct from the fractions evaporating in the air or being deposited onto the soil surface. Because these fluxes were not directly measured, all the metered water applied during CC was conservatively treated as consumable blue water. This choice avoided the application of unsupported irrigation efficiency coefficients for the micro-sprinkler treatment and preserved internal consistency in the comparison with drip irrigation. Indeed, irrigation efficiency can vary markedly with system design, weather and management, and even precision irrigation systems cannot be assigned reliable generic coefficients without site-specific measurements (Muratoglu et al., 2023).

The last limitation concerned the estimation of WF_{grey} . No soil analyses were available at the beginning of the trial to determine the baseline nitrogen concentrations. According to this, the initial soil nitrogen content was assumed to be zero in both treatments. This assumption preserved the comparability between irrigation treatments rather than claiming the true absence of residual soil nitrogen. WF_{grey} estimates are known to be influenced by assumptions on background concentrations and, especially, by the coefficients used to estimate nitrogen leaching. Several recent studies showed that conventional or constant-coefficient approaches can diverge widely from field-based or model-based estimates, because nitrogen losses vary with soil texture, climate, irrigation method, and crop management (Muratoglu, 2020). For this reason, nitrogen leaching was estimated indirectly using literature-based equations by Franke et al. (2013). Since fertilization management and nitrogen balance were the same in both experimental areas, any systematic bias associated with this approach affected both treatments similarly, thereby limiting its effect on the relative comparison between irrigation systems.

4.4. Water footprint mitigation strategies

Most WF assessments focus on the WF_{blue} and WF_{green} , undervaluing the impact of WF_{grey} , because of its lower influence on the total (averagely 10% observed on artichoke) despite its environmental significance, since nitrate water pollution is a serious threat to sustainability of modern agriculture (Bijay-Singh and Craswell, 2021; Hoekstra and

Mekonnen, 2012). Shifting from inorganic fertilizers to manure, no tillage and deficit irrigation decreases the WF_{grey} dramatically but require a trade-off between WF and yield reduction (Chukalla et al., 2018).

The water saving potential is usually pursued by reducing the water supply for irrigation rather than reducing evapotranspiration or collecting rainwater (Gao et al., 2023). The crop evapotranspiration can be reduced significantly by introducing irrigation technologies (Huang et al., 2020; Wei et al., 2022) such as CC, that include the reduction of leaf temperature, hence a decrease of evapotranspiration of artichoke (Deligios et al., 2019). In addition, reservoirs contribute to the efficient water use by collecting run-off water from the soil during intense or extreme precipitation, reducing environmental and economic costs of irrigation. The WF can be mitigated also with deficit irrigation, mulching or tillage practices enhancing the soil water retention (Kader et al., 2019) to increase WF_{green} and reduce WF_{blue} . The mulching includes the use of innovative compounds such as hydromulching obtained from recycled additives, that enhance the water retention by reducing the soil salinity (Romero-Muñoz et al., 2024). Improving the physical properties of the soil reduces erosion and increases the effective precipitation, resulting in a lower impact of WF_{blue} . In fact, the volumes of water available for evapotranspiration are controlled by the soil characteristics and the rooting depth of the plant (Mialyk et al., 2024). The application of deficit irrigation on artichoke allowed a water saving up to 50% and a yield loss limited to 10% (Alromeed et al., 2015), whereas in other crops such as corn, a 20% deficit irrigation coupled to mulching did not result in significant yield reduction (Gao et al., 2023).

The increasing frequency of heat waves are expected to cause more damage to agriculture than the increase of the average temperature (Gutschick and BassiriRad, 2010). The irrigation strategies will be increasingly important for protecting artichoke from heat stress, including climate-controlled irrigation or supplementary irrigation. The WF has been an important tool for assessing the environmental sustainability of alternative irrigation managements on the artichoke production chain to foster the sustainable allocation and saving of water resource. The CC management proved to be effective in mitigating the yield reduction and increase the crop resilience to climate change without affecting the environmental impact in terms of water use. Further investigation could be conducted on the effects of CC irrigation on soil temperature, with implications on its heat balance, water evaporation dynamics and soil fertility.

5. Conclusions

The cultivation of globe artichoke in semi-arid regions raises questions about the sustainable use of water resources. The application of forcing techniques for early production increase the water consumption and exposes artichoke to heat stress and potential yield losses. The agronomic and environmental impact of irrigation can be assessed with a water footprint analysis of the water consumed per unit of fresh yield. The three-year experimental trials on globe artichoke demonstrated that the irrigation management with canopy-cooling provided using mini-sprinklers did not affect significantly the water footprint compared to conventional drip irrigation. This was due to an increase of yield more than proportional to the increase of the total water use, achieved by reducing the thermal stress on the plants mainly through a significant reduction of the head atrophy incidence. The water footprint of the canopy-cooling irrigation management was $888 \text{ m}^3 \text{ t}^{-1}$ and comparable with former studies on artichoke. The environmental sustainability and effectiveness of canopy-cooling was strictly related to the summer climate conditions: the canopy-cooling management mitigated the yield reduction and compensated the higher water use only in case of a significant heat stress in summer above 135 SDD during the irrigation period. Canopy-cooling irrigation was demonstrated to have an important role in protecting the crops, ensuring food security and sustainability of the agroecosystems, but it was effective only under severe heat

stress conditions, where it significantly reduced the head atrophy incidence. For this reason, forecasting potential heatwaves can support the farmer in assessing whether to use canopy-cooling to relieve the heat stress of horticultural crops with a rational and sustainable use of the water resource.

The results observed on artichoke can be expected also on other summer intensive horticultural crops that do not currently benefit from cooling irrigation technologies that, by contrast, are commonly adopted in greenhouse horticulture and floriculture (cooling or fog systems). Some limitations can be encountered when calculating the WF of CC management at farm-scale, where the spatial configuration of the commercial CC irrigation system may not allow plot replications due to the mist drift in the adjacent plots or irrigation treatments. Furthermore, the fraction of total water distributed in the CC treatment that provided the actual cooling effect could not be precisely quantified, and the application of precision irrigation technologies complicated the precise estimation of the WF_{blue} component. Additional researches should focus on integrating agronomic performance with economic analysis, energy consumption and life cycle assessment (LCA) to provide a more comprehensive perspective of the sustainability of canopy-cooling irrigation systems. Such multidisciplinary approaches would support the development of optimised and alternative irrigation strategies that balance crop productivity, resource use efficiency and environmental impacts.

CRedit authorship contribution statement

Marco Cossu: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Formal analysis. **Maria Teresa Tiloca:** Methodology, Investigation, Data curation. **Stefania Solinas:** Writing – review & editing. **Stefano Lupinu:** Data curation. **Andrea Cossu:** Visualization, Formal analysis. **Paola A. Deligios:** Writing – review & editing, Project administration. **Luigi Ledda:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of Competing Interest

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

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Data availability

Data will be made available on request.

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