



Phenology and Fruit Growth Dynamics of Mango (*Mangifera indica* L.) in Greenhouse and Open Air in Mediterranean Climate

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Abstract Phenological evolution of shoots and fruit growth of three mango varieties—*Keitt*, *Osteen* and *Tommy Atkins*—were monitored during two reproductive seasons, from full flowering to fruit harvest on trees cultivated in the open air and inside a greenhouse, in the island of Sicily—Italy. The aim of the study was to assess the behavior of mango trees subjected to summer high temperatures under a permanent plastic cover in the Mediterranean climate. Differences between open air and greenhouse emerged in the dates of first record of major phenological stages and in their duration, and in the fruit growth rates. Greenhouse cultivated trees showed a significant anticipation of flowering and ripening of the fruits respect to open air trees, with

harvest conducted earlier during the season. On the other hand, open air cultivated trees achieved fruit maturity in a shorter time compared to the greenhouse, with fruits needing between 90 and 110 days after full flowering to reach their final dimensions—while the trees in the greenhouse needed at least 125 days. The study allowed to understand the growth dynamics of mango fruits subjected to extreme high temperatures and provides new information to evaluate the opportunity of greenhouse cultivation of mango in the Mediterranean climate.

Keywords BBCH scale · Fruit growth rate · *Keitt* · *Osteen* · *Tommy Atkins*

Significance statement Mango can be grown in different areas of the world using the right cultural techniques, and greenhouse cultivation is one of these. However, it is necessary to understand the physiological behavior of the plant grown in this condition and to assess whether this technique is profitable and sustainable for the grower.

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Introduction

Climate change happening in recent years has stimulated the cultivation of numerous tropical species in the Mediterranean basin. Among these, Mango (*Mangifera indica* L.) presents the largest increase in its cultivation area, due to its good productivity, popularity among European consumers and adaptability to different environments [1, 2]. Nevertheless, even in coastal areas, low temperatures in Mediterranean winters can lead to unrecoverable damages to mango, especially to young plants [3, 4].

In fact, growers of mango in the Mediterranean basin need to protect plants from frost until they have hardened. This causes higher material and maintenance operation costs for the grower [5]. One viable alternative to keep the plants safe from low temperatures is the cultivation in protected environment, which, on the other hand, is an established reality in Japan and Spain, where some of the most appreciated mango fruits are produced [6, 7]. The greenhouse cultivation of mango, though, raises the issue of the extreme

high temperatures that can occur in summer season in the Mediterranean climate, where summers are typically hot with daily average temperatures that can stay above 30 °C for various days. Few studies investigating the growth of mango plants in greenhouse in the Mediterranean areas [8–10] were conducted before the publication of the BBCH scale for this species [11] and few information on plant phenology and fruit growth dynamics could be found in the literature.

Therefore, the aim of the study was to assess the behavior of mango trees and the dynamics of fruit growth when subjected to summer high temperatures under a permanent plastic cover in the Mediterranean climate.

Material and Methods

The experiment was conducted for two years—2019 and 2021—on adult mango trees of the cultivars *Tommy Atkins*, *Osteen* and *Keitt*. These varieties are respectively early, middle and late ripening.

Environmental Conditions and Plant Material

The trial was conducted in two orchards (Fig. 1), both located in the area of Sant’Agata di Militello (ME, Italy, 38°04’N14°38’E): the first one (open air) at 6 m above sea level (a.s.l.) and the second one (greenhouse) at 9 m (a.s.l.). Plants of the open air orchards were six years old, while plants of the greenhouse were four years old. The climate of the area can be considered as Mediterranean according to the Koppen classification [11].

The greenhouse had a ceiling made of poly(methyl methacrylate) sheets and side walls in polyethylene film, and it was equipped with an automatic ridge and walls opening system activated by a temperature sensor. The plants in both orchards are grown according to the standard cultivation practices and fertilized with the same protocols. The shoots that were studied were all produced in the current year.

Open air and greenhouse temperature data were collected using temperature sensors equipped with a data logger (Elitech RC-4, Elitech LTD, London, UK).

Experimental Design

A factorial experiment design $2 \times 2 \times 3$ (2 years, 2 field conditions, 3 varieties) was adopted.

Five plants per variety for a total of 15 plants were randomly chosen and marked in the open air and greenhouse fields, respectively. On each plant, 5 shoots per exposition (N-S-W-E) were chosen and labelled, for a total of 20 shoots per plant and 100 shoots per variety.

Data Collection

The selected shoots were photographed at two-weeks intervals with a DSLR camera and the photos were compared with the images and descriptors used by Hernández-Delgado et al. (2011) on the reference BBCH extended scale for mango [12] to identify the exact phenological stage. The prevailing phenological stage for each date was assumed to be the mode value among all observed shoots. Percentage of expression of the mean phenological stage on the experimental orchard was obtained, and it was used to determine the precise moment of full flowering (stage 615 with a percentage of expression on the whole field higher or equal to 50%) (Fig. 2). Average length, in days, of each major phenological stage was also computed for each shoot of each cultivar in the two orchards.

After fruit set took place, 2 fruits per marked plant—for a total of 10 fruits per variety—were labelled in the open air and in the greenhouse orchards respectively, for a total of 30 fruits per orchard. Length, width and thickness of the fruits were measured at two-weeks intervals with a digital caliper (TR20040, TrTuroni, Forlì, Italy). Measurement of the fruit dimensions started after thickness had a minimum value of 2 cm, this in order not to lose samples due to the physiological fruitlet drop or cause manipulation damages to the young fruits. Average Fruit Growth Rate (AGR) at all measurement intervals was obtained for each variety as the mean value of the relative growth rates (RGR) for each of the three dimensions, measured as:

$$\text{RGR} = \frac{(x_{n+1} - x_n) \times 100}{x_n} \quad (1)$$

where x refers to any of the three measured parameters, n is any measurement date and $n + 1$ is the following measurement date.

Measurements of the shoots’ phenological data and of the fruits’ dimension were carried out until fruits were harvested or their AGR was below 2% for two consecutive measurements.

Statistical Analysis

Statistical analysis was carried out using Sigmaplot 14.0 Statistical Software (Systat Software, Inc., San Jose, CA, USA) and R software [13]. Significant differences ($p \leq 0.05$) between the groups of the two experimental stations were evaluated by means of Student’s and Welch’s t -tests.

Results and Discussion

Temperature Trend

Maximum temperatures in the greenhouse remained higher than in the field for the whole recorded period in both



Fig. 1 Plants of the field (left) and greenhouse (right) orchards

Fig. 2 Shoots of the cvs *Keitt*, *Osteen* and *Tommy Atkins* photographed at full flowering (BBCH stage 615) in the field **a, b, c** and in the greenhouse **d, e, f**, respectively



years, while no major differences were found between the minimum temperatures recorded in the two experimental orchards (Fig. 3). Therefore, the greenhouse ensured a consistent heat gain to the plants placed below it during spring and summer.

The absolute maximum temperatures, in the first year, were 47.7 °C (recorded on July 9th) and 40.2 °C (recorded

on June 25th) in the greenhouse and open air respectively, while, in the second year, a temperature of 50.2 °C was reached on August 1st in the greenhouse and, in the open air, a temperature of 39.7 °C was reached on June 17th. No visual damage was observed on the plants following these extreme high temperatures. Absolute minimum temperatures in the period of observation were 9.3 and 10.4 °C (both recorded

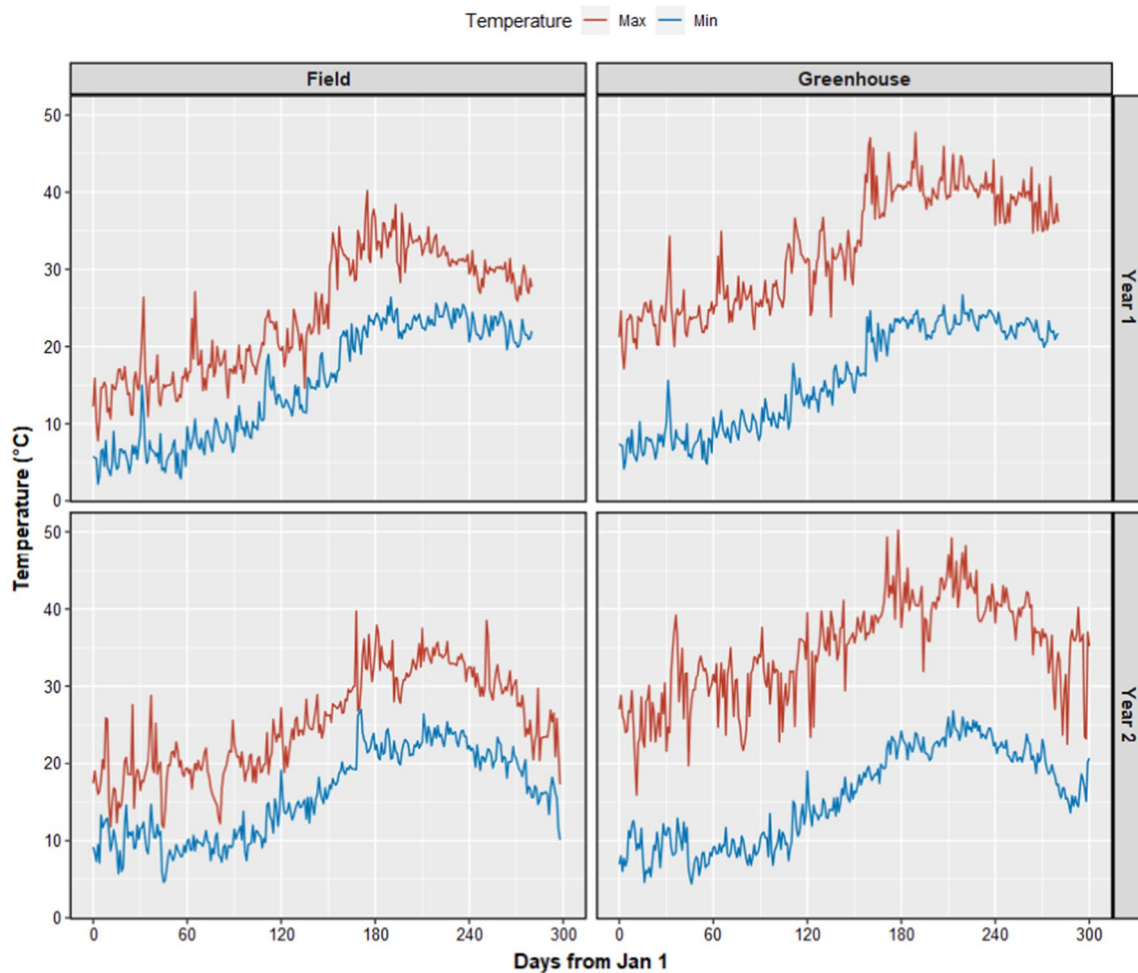


Fig. 3 Time course of the daily minimum (blue) and maximum (red) temperatures recorded in the field and in the greenhouse over the monitoring periods in year 1 and year 2 (color figure online)

on April 19th) in greenhouse and field respectively during the first year, and 7.0 °C (March 26th) and 6.2 °C (March 17th), in the greenhouse and field respectively in the second year. Temperatures didn't fall below 4 °C, which is considered to be the lower limit before chilling damages start occurring in mango buds [3]. This is an important information, considering that the climate of the northern coast of Sicily is often subjected to late returns of cold temperatures that may occur until the end of April [14].

Hence, if, on one hand, the greenhouse cultivation allowed the growers to proceed to an early harvest of the fruits, which can be sold at a higher price on the market, it also created the conditions for possible damage to the plants. In fact, mango is known to tolerate temperatures up to 48 °C for a short time without being adversely affected [4], but damages to the photosynthetic machinery can happen already at 45 °C [1]. Considering that summers in the Mediterranean Basin are becoming increasingly and unprecedentedly hotter [15], as proven by the recent European record

of air temperature of 48.8 °C occurred in August 2021 in Sicily, plants kept below a permanent plastic cover could experience conditions of thermal stress that threaten their health and productivity.

Phenological Evolution

In both years of observation, shoots of the greenhouse reached the three phenological stages of flowering, fruit set and maturity with a significant anticipation on the calendar date with respect to the open air (Fig. 4). Similar results were obtained by several authors [1, 8, 16], who observed how increasing average and maximum temperatures anticipate mango phenological phases and fruit maturity.

The plants of all varieties grown in the greenhouse reached full flowering—phenological stage 615—within the end of the month of April in both years of observation, while the plants of all varieties growing in the open air reached the same stage between May 13th and 30th, regardless of the

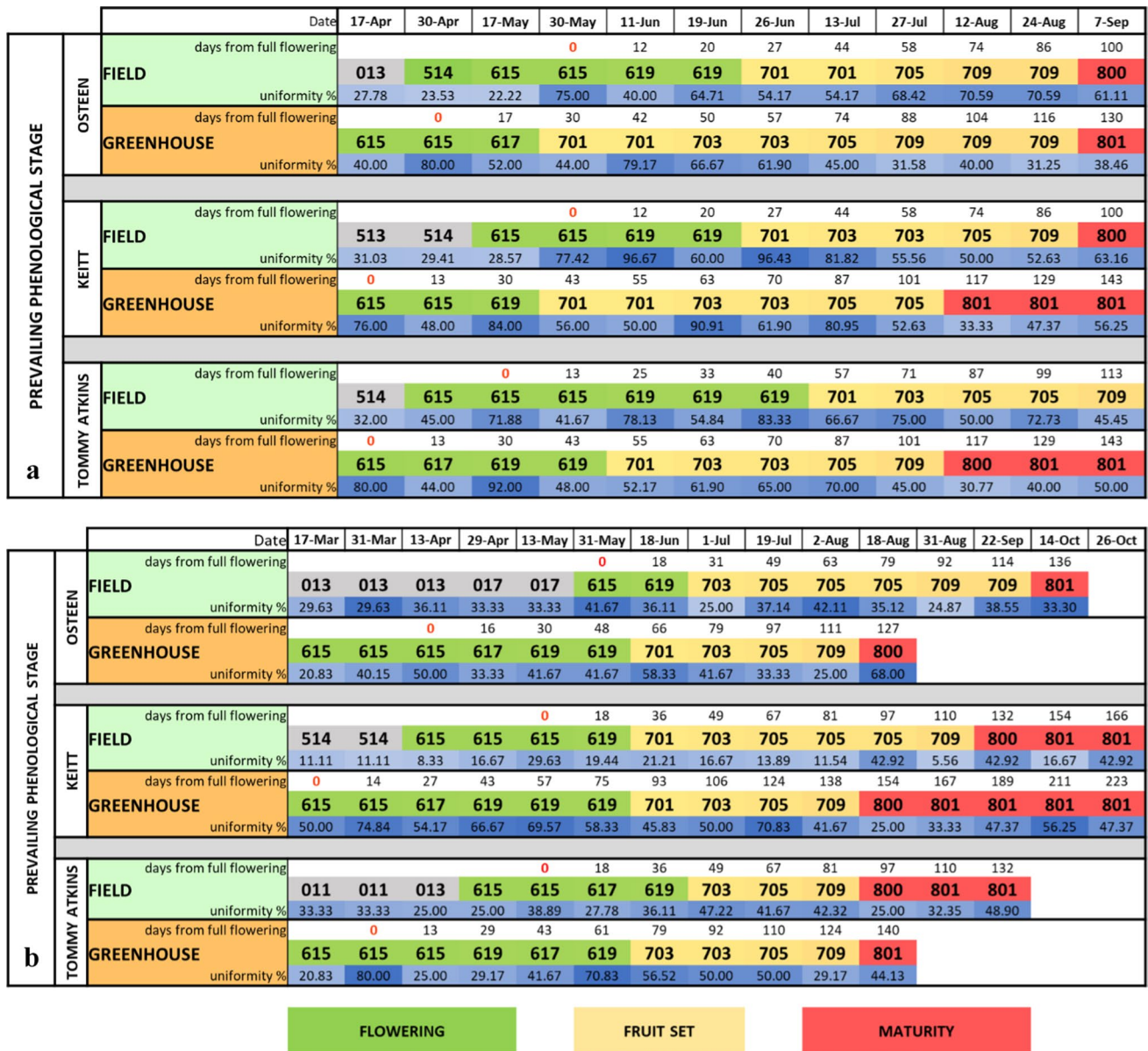


Fig. 4 Prevailing phenological stages for the three studied cultivars in the field and greenhouse experimental stations over year 1 **a** and 2 **b**. Uniformity % indicates the percentage of shoots in the prevailing phenological stage on the total number of observed shoots

year of observation. It is worth noting that the difference in the moment of full flowering between open air and greenhouse was always of one month at least, and up to 56 days in cv. *Keitt* in year 2 (Fig. 4b).

The phenological stages advancement reached in the greenhouse respect to the open air can be ascribed to the higher average temperatures, which determined an earlier full flowering. In fact, statistical analysis (Table 1) confirms that the phenological stage of flowering (610–619) persists on the plants of the greenhouse for a significantly longer period compared to the field, with differences up to 36 days, in both years of observation.

In conclusion, we could confirm that the advancement of phenology of the mango growing in the greenhouse should be attributed to the anticipation of the moment of full flowering, rather than to an acceleration of the general activity of the plant over the reproductive season. This is a well-known consequence of the cultivation at warmer climates [16]. The longer duration of the subsequent phenological macro-stages, poses the question of the exposition of inflorescences, fruitlets and fruits to conditions of stress, such as extreme temperatures and water stress [17, 18], or biotic and abiotic threats, such as insect infestation or sunburn [19–22].

Table 1 Length, in days, of major phenological stages for each cultivar in the two experimental stations for the two years of observation

Year	KEITT					OSTEEN					TOMMY ATKINS				
	FIELD		GREENHOUSE		*/ns	Field ±		Greenhouse ±		*/ns	Field ±		Greenhouse ±		*/ns
Stage	Length (days)	sd.	Length (days)	sd.		Length (days)	sd.	Length (days)	sd.		Length (days)	sd.	Length (days)	sd.	
610–619	30.47	12.85	35.42	6.55	ns	25.87 ^b	10.53	35.75 ^a	9.67	*	33.89	11.84	40.71	16.04	ns
700–709	48.19	22.06	45.19	23.47	ns	45.09 ^b	19.05	62.09 ^a	30.47	*	56.06	25.27	46.63	29.33	ns
800–809	20.00 ^b	6.93	36.53 ^a	20.20	*	14.00 ^b	0.00	31.00 ^a	15.31	*	20.00	8.49	22.14	13.18	ns
Year 2	KEITT					OSTEEN					TOMMY ATKINS				
	FIELD		GREENHOUSE		*/ns	Field ±		Greenhouse		*/ns	Field ±		Greenhouse		*/ns
Stage	Length (days)	sd.	Length (days)	sd.		Length (days)	sd.	Length (days)	sd.		Length (days)	sd.	Length (days)	sd.	
610–619	49.83 ^b	14.53	79.87 ^a	26.04	*	24.13 ^b	2.89	60.68 ^a	31.13	*	36.04 ^b	16.02	59.6 ^a	25.59	*
700–709	48.33	40.86	44.00	13.39	ns	28.53 ^b	9.81	37.81 ^a	16.45	*	26.39 ^b	9.73	41.13 ^a	13.98	*
800–809	56.33 ^b	25.58	71.21 ^a	7.23	*	31.67 ^a	9.67	15.21 ^b	0.43	*	46.17 ^a	11.29	15.27 ^b	0.88	*

Values for each cultivar’s shoots were tested by means of Student’s *t*-test.*= values differ significantly ($p < 0.05$); ns = values do not show statistically significant differences ($p > 0.05$)

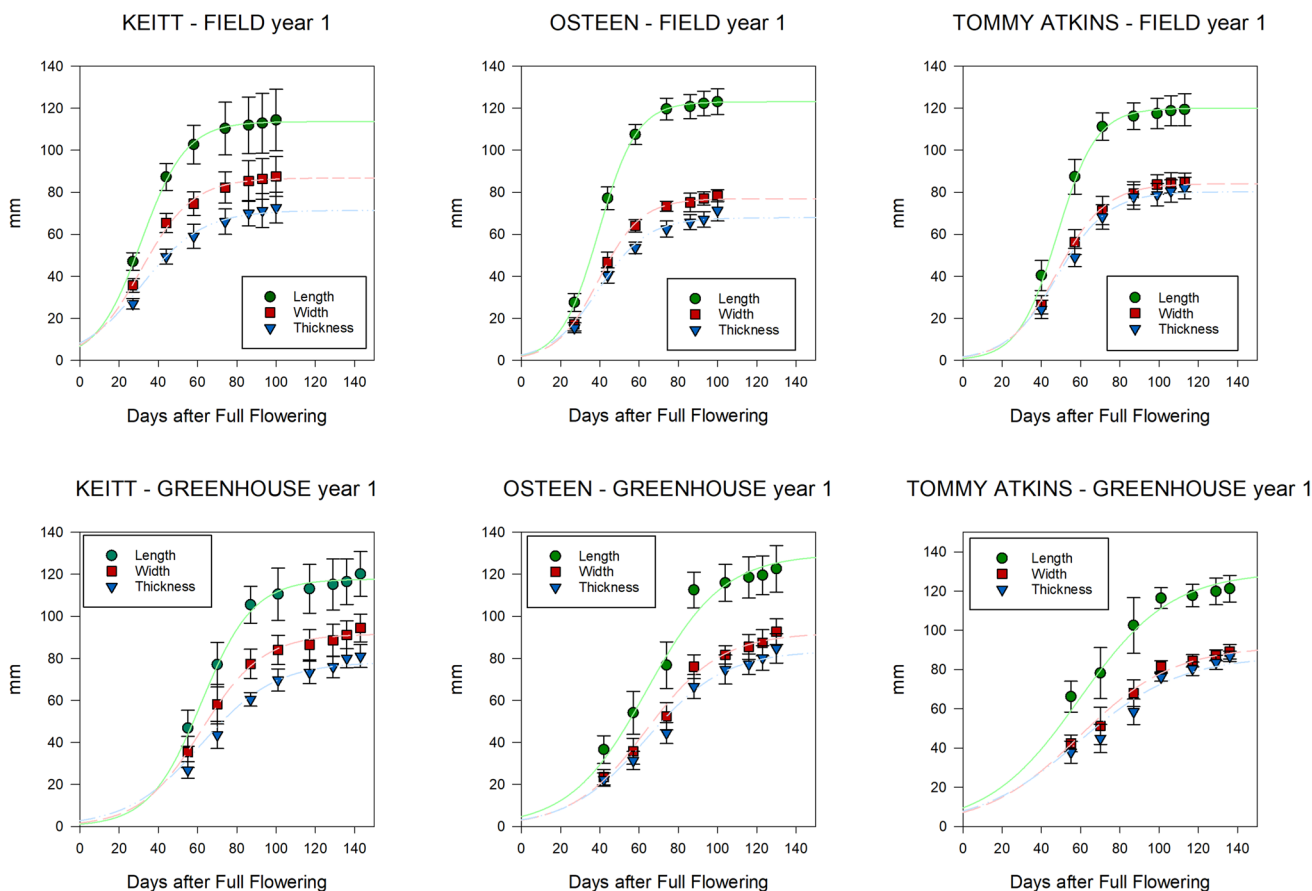


Fig. 5 Evolution of Length, Width and Thickness of the labelled fruits for the three cultivars in the two experimental stations over the observation period during the first year, in relation to the number of

days after full flowering. Data are presented as mean ± standard deviation ($n = 10$) and trend curves are plotted within the chart

Fruit Dimensional Growth

The fruit growth, in terms of length, width, and thickness, followed the single-sigmoid model in all cultivars and in both conditions (Figs. 5, 6). In the greenhouse, fruits of all the variety presented a slower increase in the first stages of growth with respect to open field.

Fruits growing in the field reached values of thickness equal or higher than 20 mm between 10 and 25 days after full flowering. In the greenhouse, instead, it took more than 30 days independently from the variety to reach such value. *Keitt* fruits growing in the greenhouse were the latest to reach these dimensions, needing more than 55 days after full flowering in both years. Fruits of all varieties growing in the open air reached their final dimension within 110 days after full flowering, while fruits in the greenhouse completed their growth only 125 days or more after full flowering (Figs. 5, 6).

The differences in the shapes of the pattern that fruits followed during their growth that emerged between field and greenhouse for both years of cultivation, regardless of the

cultivar, are probably explained by the differences in temperature recorded in the two cultural situations, as it was pointed out by various authors [23, 24] that temperature strongly affects the rate of cell division, the main process taking place at the beginning of organ growth, of fruits of different species.

The difference observed in both years and for all cultivars in the fruit growth rates can be ascribed to the difference in temperatures between field and greenhouse. In fact, the first half of the fruit growth happened in the period between June and July, when average temperatures in the greenhouse were constantly above 30 °C and weekly maximums consistently reached values around 45 °C and above (Fig. 3). Recent studies [17, 25, 26] confirmed this effect of high temperatures on mango fruits with the use of gauges allowing continuous measurement of the diameter of the trunk and fruits [27], which are seen shrinking during the hottest hours of the day, while expanding during the fresher night hours.

Another noticeable difference between fruits growing in the open air and in the greenhouse was seen when comparing the fruits' Average Growth Rates (AGR) (Fig. 6). Fruits

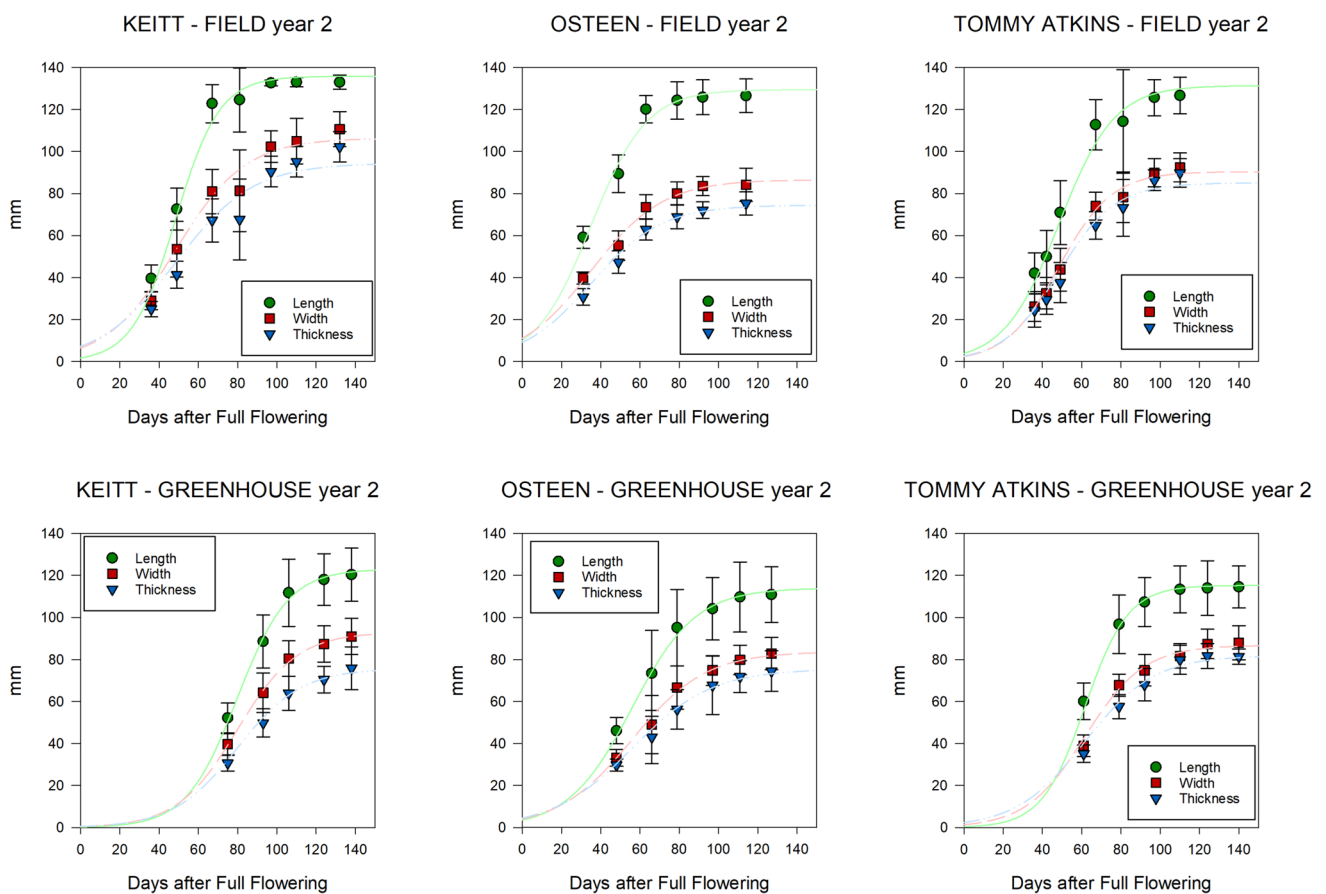


Fig. 6 Evolution of length, width and thickness of the labelled fruits for the three cultivars in the two experimental stations over the observation period during the second year, in relation to the number of

days after full flowering. Data are presented as mean \pm standard deviation ($n = 10$) and trend curves are plotted within the chart

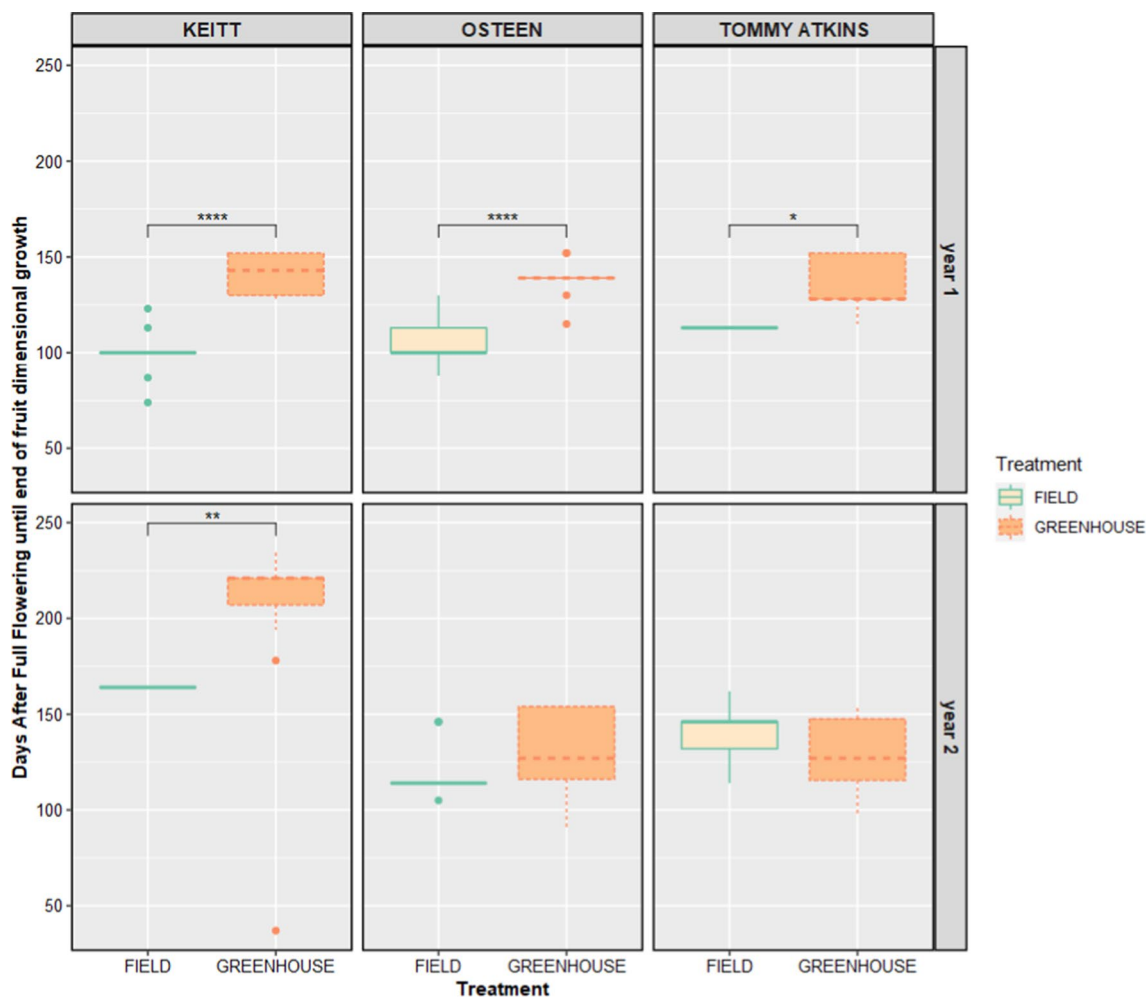


Fig. 7 Comparison of the number of days after full flowering until end of fruit dimensional growth for each variety and year of cultivation in the two experimental stations. Asterisks (*) indicate statisti-

cally significant difference between the treatments for Student's *t*-test at * $-p < 0.05$, ** $-p < 0.01$, *** $-p < 0.001$, **** $-p < 0.0001$

of all cultivars grown in the field reached higher peak values for their growth rate than the ones in the greenhouse. The latter had values that didn't exceed 63.52% (*Keitt*—year 1), while the fruits of the field reached growth rates values up to 170.71 and 109.97% (*Osteen* and *Tommy Atkins*, respectively, in year 1).

We investigated what values of maximum daily temperature could have inhibited the growth of the fruit (Fig. 7). Even though a satisfying fit to a mathematical model couldn't be found, it can be observed that the highest AGR values (> 50%) were recorded mostly when temperatures in the corresponding period didn't exceed 40 °C, while AGR tended to decrease when maximum temperatures reached values close to 50 °C, as highlighted by the locally weighted regression line (Figs. 8, 9). However, further investigation should consider more factors,

such as initial fruit dry mass and leaf-to fruit ratio, which could be limiting fruit growth, as highlighted in various occasions by Léchaudel [18–20].

Conclusion

What emerged from the two years of observation was that the expected—and achieved—anticipation of maturity of the fruits grown in the greenhouse should not be attributed to the higher temperatures reached below the plastic cover over the whole reproductive season, but rather to the anticipation of the moment of flowering, due to the higher temperatures which are recorded during the early stages of reproductive activity of the plant. In facts, we

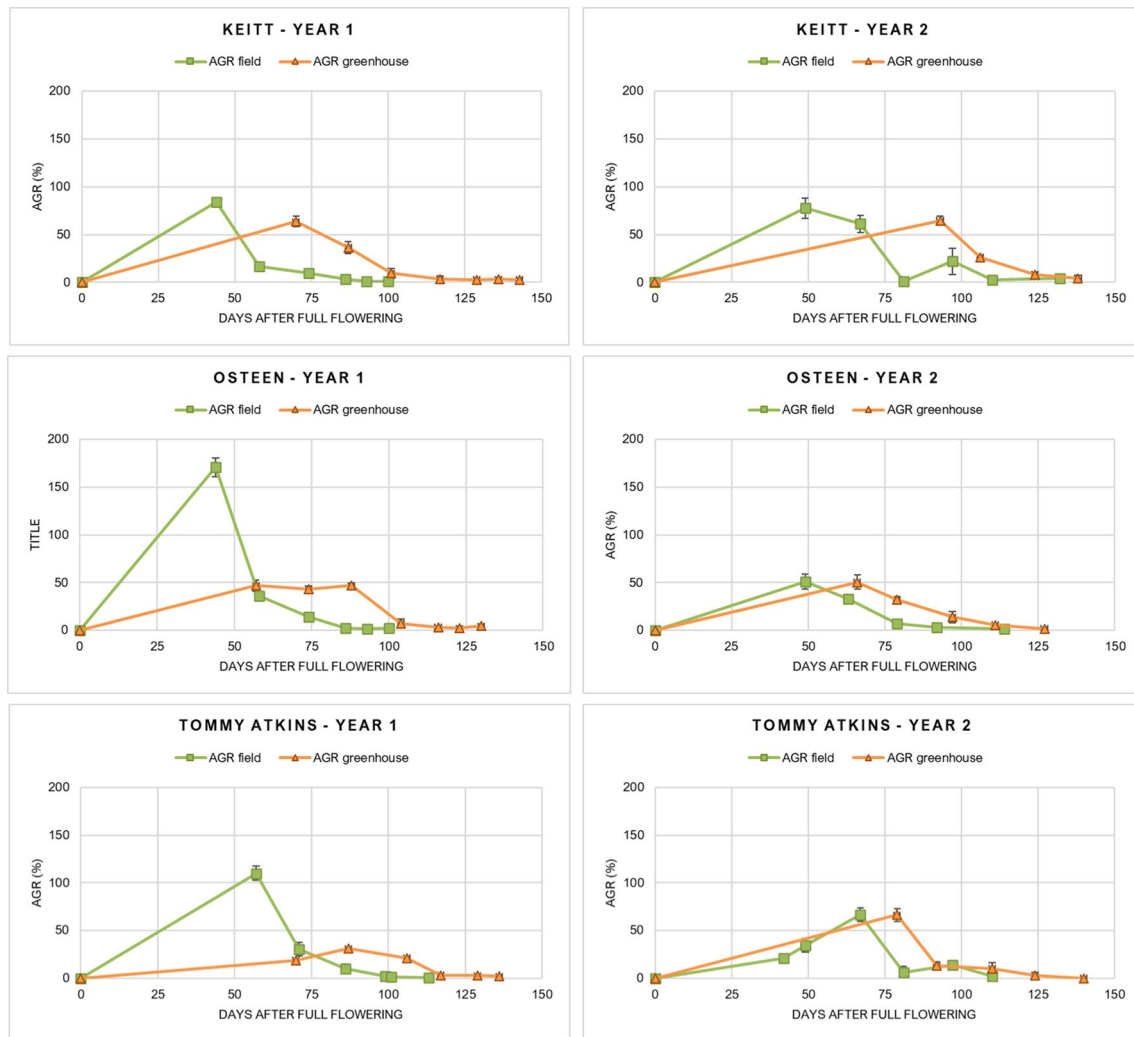


Fig. 8 Average Relative Growth Rate (AGR) of the fruits of the three varieties in the two experimental stations over the two years of observation, related to the number of days after full flowering. Data are

presented as mean value + standard deviation of the growth rate of the measured fruits ($n = 10$)

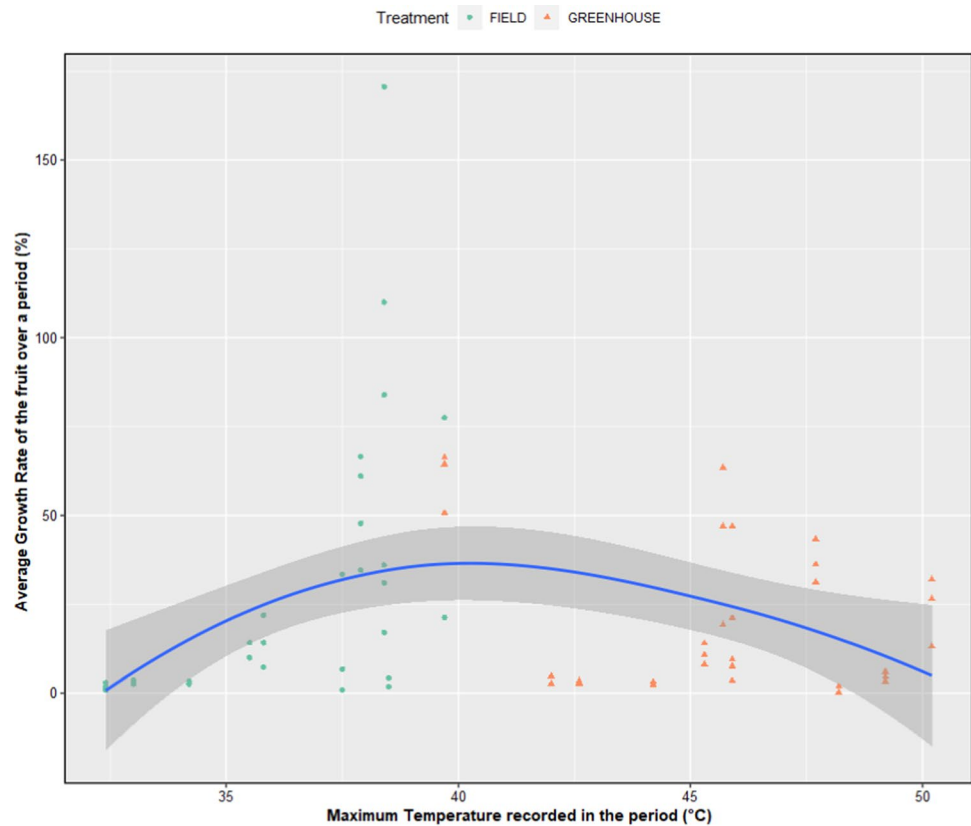
could show how, under the same climatic conditions of the northern coast of Sicily, growth of mangoes after fruit set in the open air happens in a shorter period and without stress conditions imposed by extreme high temperatures, compared to what happens for fruits of the same cultivars inside a greenhouse.

The advantages offered by the cold greenhouse cultivation with regard to protection of the tropical plants such as mango from temperate winters could therefore be neutralized by the stress imposed to the plants during hot, dry summers. Techniques for limiting the thermal gain inside the

greenhouse, such as shading or roof whitening, or the implementation of fogging or misting systems, though effective, would instead probably undermine the environmental and economic sustainability of the cold greenhouse system [28, 29], when compared to the open air cultivation.

Possibly, non-permanent protected cultivation systems could represent the adequate solution to meet the requirements of the plants and the growers who are cultivating these species in the Mediterranean, and future research could concentrate on the evaluation of these, taking into account both environmental and economic aspects.

Fig. 9 Values of the fruits' average growth rate (AGR, %) correlated to the maximum daily temperatures recorded in the corresponding period. Locally weighted scatterplot smoothing (LOWESS) line, in blue, is obtained with `geom_smooth` function in R package `ggplot2` [28, 29] (color figure online)



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Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Declaration

Conflict of interest The authors declare that they have no conflict of interest.

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