Available online at www.ijournalse.org

Emerging Science Journal

(ISSN: 2610-9182)

Vol. 7, No. 2, April, 2023

Climatic Factor Differences and Mangosteen Fruit Quality between On- and Off-Season Productions

Krisanadej Jaroensutasinee [1], Mullica Jaroensutasinee [1*], Piyatida Boonsanong [1]

[1] *Center of Excellence for Ecoinformatics, School of Science, Walailak University, Nakhon Si Thammarat, Thailand.*

Abstract

The objective of this study was to investigate the differences in climatic factors and fruit quality between on- and off-season production periods. Climate, soil, and mangosteen measurements were all studied during on- and off-season production. We chose 40 mangosteen trees and observed flowering and fruit set rates over two production periods. The results showed that the number of flowers per branch, the number of fruits per branch, the circumference of fruits, and the fruit weight were higher during the on-season mangosteen production period than during the off-season mangosteen production period. However, the number of edible pulp segments, peel thickness, percentage of translucent flesh, and fruit gumminess were lower in the on-season mangosteen production period than in the off-season mangosteen production period. The percentage of fruit scars did not differ between the on- and off-season mangosteen production periods. When compared to the on-season mangosteen production period, there was lower relative humidity, soil moisture at 120 cm depth, and leaf wetness at 15 cm above ground during the off-season mangosteen production period; however, there was higher air temperature, soil moisture, and soil temperature at all four depth levels.

Keywords:

Off-Season;
On-Season;
Flowering;
Fruit Quality;
Mangosteen.

Article History:

Received:	18	October	2022
Revised:	02	December	2022
Accepted:	26	December	2022
Available online:	22	February	2023

1- Introduction

Mangosteen (*Garcinia mangostana* L.) is a major fruit crop in Thailand, with an increase in export value of over 88 billion USD since 2012 [1]. Thailand is the largest grower of mangosteens, with a planting crop area of over 70,900 ha and production of 351,760 tons/year [2]. Mangosteens have a short harvesting season, which results in oversupply, a heavy marketing burden, and a decrease in fruit prices. Growers are highly desired to extend the season of mangosteen production because the price of mangosteens in the off-season is always higher than that in the on-season. Therefore, to increase income for growers and meet the demand for year-round exportation, approaches for flowering induction of mangosteens are in demand.

The pattern of reproductive phenology in mangosteens correlates with several abiotic and biotic factors. Many studies have shown that mangosteen reproductive phenology (i.e., flowering and fruiting) is associated with climatic conditions (e.g., rainfall, temperature, radiation levels, and photoperiod), height above sea level, availability of shade, and geographical locations [2–8]. Drought-inducing flowering has been reported in several plant species, including citrus fruits [9], durian [10, 11], lime [12], longan [13], loguat [14], mango [15], and mangosteen [5, 16, 17]. Many studies have reported that drought-inducing flowering in mangosteens with 15-30 dry days for flower bud formation and flowering, occurs naturally after the dry period [2, 3, 5, 17-19]. Stress from drought causes carbohydrates to accumulate in the leaves [20]. However, the stresses resulting from the drought that affect flowering in mangosteens have not been thoroughly investigated.

* **CONTACT**: mullica.jn@gmail.com

DOI: http://dx.doi.org/10.28991/ESJ-2023-07-02-020

Precision agriculture using sensors to monitor soil, plants, and weather conditions enables growers of mangosteens to induce flowering during the off-season mangosteen production. This requires monitoring and control strategies for soil moisture conditions, changing weather patterns, and plant physiological conditions. Production of off-season mangosteens is possible in drought-inducing flowering studies. High-quality fruits for export are limited by fruit defects such as small fruit size, translucent flesh disorder, and gamboge disorder [21]. However, there are limited studies on off-season mangosteen production and fruit quality. This study is the first to investigate the climatic factors affecting the mangosteen flowering period and fruit quality during the on- and off-season production periods. The two main objectives of this study were (1) to investigate climatic factor differences between the on- and off-season periods and (2) to investigate fruit quality differences between the on- and off-season periods. The results of this study will help us gain a better understanding of how to induce off-season mangosteen production and improve fruit quality. The flowchart of the research methodology that was used to achieve the study's aims is shown in Figure 1.

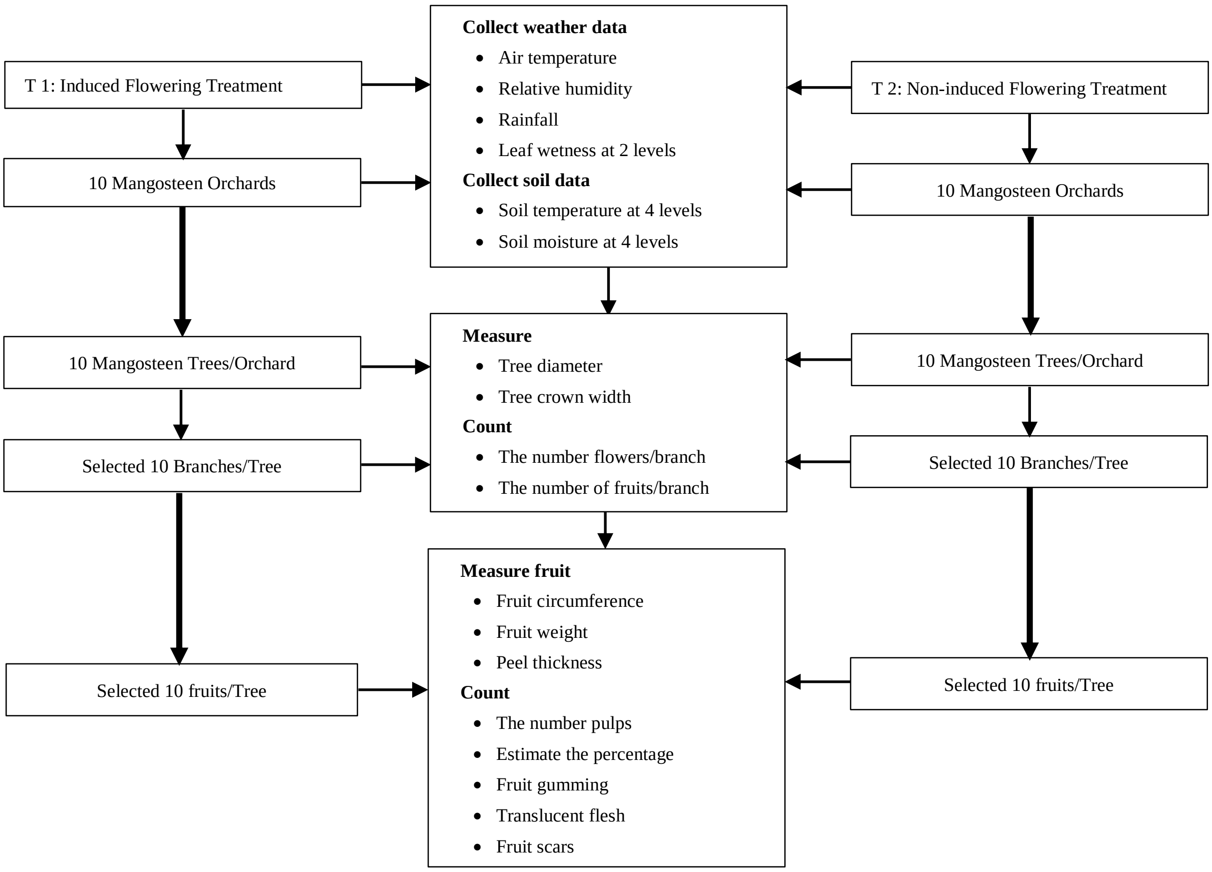

Figure 1. Research methodology on climatic factors and mangosteen fruit quality between on and off-season productions

2- Materials and Methods

2-1- Study Area

This study was conducted at a mangosteen orchard (latitude 8.357614°N, longitude 99.861444°E) in Lansaka District, Nakhon Si Thammarat Province, and Southern Thailand (Figures 2-a and 2-b). This mangosteen orchard has 20–30-year-old mangosteen trees, with approximately 100 trees in an area of 1.6 ha.

2-2- Mangosteen Biology

Mangosteen (*Garcinia mangostana* L.) is a tropical tree native to Southeast Asia, mainly in Malaysia, Myanmar, Thailand, Cambodia, Vietnam, and the Sunda Islands [2]. Mangosteen has no genetic variation, because it propagates apomictically. Mangosteen has high orchard establishment costs owing to its long juvenile period and slow growth [22]. Vital mangosteen production occurs in Southeast Asia, particularly in Thailand. Thailand has the highest mangosteen planting crop area, estimated at 4,000 ha in 1965, which has increased to over 70,900 ha by 2021, with a total yield of 351,760 tons/year. Mangosteens grow successfully on various types of soils [23, 24], but they grow well in porous sandy loam to sandy clay loam soil that is high in organic matter and well drained [21, 24, 25]. Soils in mangosteen orchard in the Southern Thailand were moderate to highly acid with soil pH ranged from 3.50-5.72 and had the P, K and Ca concentrations about 2.45-61.69 md kg^{-1}, 0.10-0.26 and 0.09-2.43 cmolc kg^{-1} [21, 26]. Under dry conditions, mangosteens require irrigation and mulch [27].

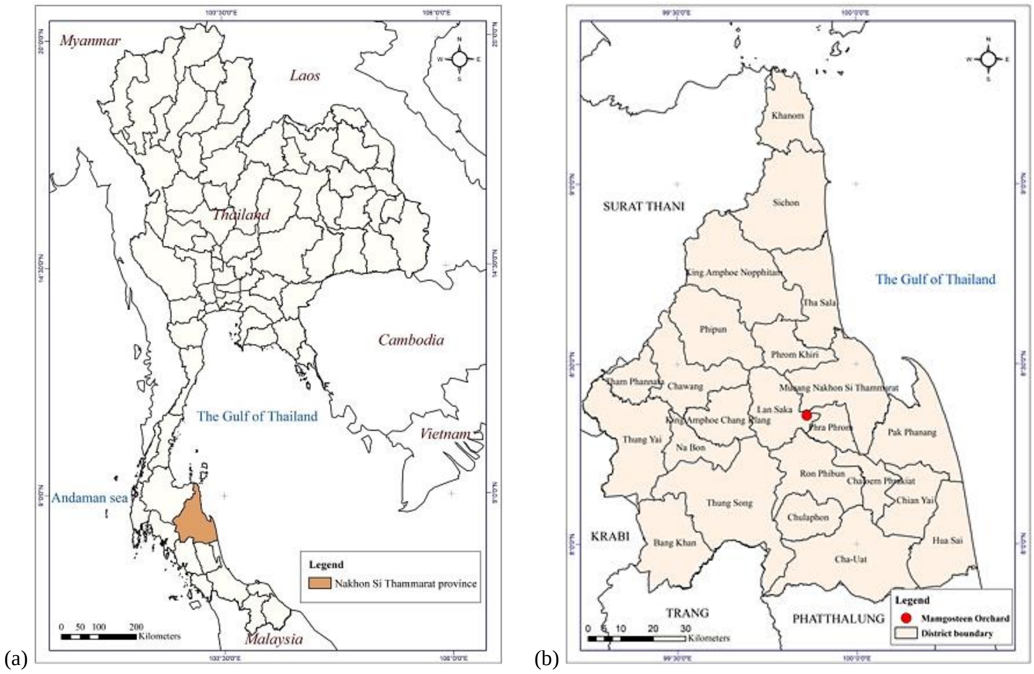

Figure 2. (a) Thailand map with Nakhon Si Thammarat Province in shaded color and (b) Nakhon Si Thammarat Province map with Mangosteen orchard location in a red dot

Mangosteen trees have a pyramidal shape with symmetrical branches are 10-25 m in height [22]. The trees begin to bear fruits 10-12 years after the seedling. The diameter of the mangosteen fruit is 5.08-7.62 cm with a thick reddish-purple rind that covers white, soft, juicy, sweet, aromatic, and edible segmented pulps [28, 29]. Mangosteen fruits weighing greater than 80 g/fruit with a fresh green calyx, unbroken peduncle, no insect damage, no translucent flesh disorder, and no gamboge disorder are indices of market-able quality mangosteen. Mangosteen trees grow and produce fruits at 25-35°C, above 80% relative humidity, and above 1,270 mm annual rainfall; however, growth is retarded at temperatures below 20°C, and sunburn occurs at temperatures above 38-40°C [2, 30]. Mangosteens in Thailand are cultivated in two regions: eastern and southern. In the eastern region, the on-season period begins in September and is harvested from April to June [17, 22]. Mangosteens in the southern region begin flowering in March and are harvested annually from July to September. In some years, mangosteens in the southern region produce off-season flowering in September, and are harvested in January-February. The quality of the fruit produced differs depending on the season and growing conditions [31]. Mangosteen production in Thailand may increase in years with longer drought periods [17].

2-3- Data Collection

An automatic weather station and two soil stations (*Davis Vantage Pro 2 Plus Model*) were installed to collect weather and soil data, consisting of maximum and minimum air temperatures, relative humidity, amount of rainfall, soil moisture, soil temperature, and leaf wetness. Weather and soil data were recorded online in real time every 15 min from March 2020-February to 2021. Soil moisture was measured using watermark soil moisture sensors installed in the soil at specific root depths. Watermark soil moisture sensors are electronic resistance sensors that measure soil moisture on a scale of 0 (saturated soil) to 200 cb (dried soil). Soil moisture and temperature sensors were deployed at four measurement depths: 15, 45, 90, and 120 cm.

The leaf wetness sensors were electronic resistance sensors that measured the presence of surface moisture on the foliage and calculated the duration of wetness. When moisture is present, the sensors detect an electrical resistance change between the gold-plated elements of the grid on a scale of 0 (completely dry) to 15 (saturated wet). Leaf wetness sensors were deployed at two heights: (1) 15 cm above the ground floor to measure leaf wetness at the floor level and (2) 160 cm above the ground floor to measure leaf wetness within the mangosteen canopy.

Climatic factors, soil factors, and mangosteen measurements were studied during two mangosteen production periods: (1) on-season production (March-August 2020) and (2) off-season production (August 2020-February 2021). Each mangosteen production period was divided into two observational periods: (1) the dry period and (2) the flowering period. In the on-season of mangosteen production, the dry period occurred during 1-24 March 2020 (25 days), the flowering period during 1-30 April 2020, and the harvesting period from 15 July-18 August 2020. In the off-season of mangosteen production, the dry period occurred from 20 August-14 September 2020 (26 days), the flowering period from 1-30 October 2020, and the harvesting period from 1-25 February 2021. Climatic data were collected during the study period (March 1, 2020, to February 28, 2021).

We randomly selected 40 mangosteen trees and measured their diameters at breast height (1.5 m above ground) and crown width in four directions (north, south, east, and west). We randomly selected ten branches per tree from the 40 selected trees, with a total of 400 branches. We counted the number of flowers per branch, number of fruits per branch, starting date of the flowering period, starting date of the harvesting period, harvesting duration, and flower blooming to harvest duration during the on- and off-season mangosteen production periods. After the mangosteen fruits were mature, we randomly selected ten fruits per tree, with a total of 400 fruits per mangosteen production, to measure fruit weight, fruit circumference, and peel thickness. Fruits were cut when they reached the edible ripening stage. The number of edible pulp segments per fruit was determined. The percentage of fruit gumming, translucent flesh, and fruit scars was calculated as a percentage in the on-season and off-season mangosteen production periods.

2-4- Data Analysis

T-tests were used to analyze (1) the mean climatic and soil factor differences between the on- and off-season mangosteen production periods and between the dry and flowering periods within each mangosteen production period, and (2) the mean mangosteen parameter differences between the on- and off-season mangosteen production periods. One-way ANOVA tests with post-hoc Bonferroni adjustments were used to test soil temperature and soil moisture.

3- Results

3-1- Mangosteen Parameters between On- and Off-Season Mangosteen Production Periods

The mangosteen trees had an average (±SD) DBH of 56.18±10.93 cm and an average (±SD) crown width of 3.41±0.44 m. During the on-season mangosteen production period, the flowering period occurred from 1-30 April 2020 and the harvesting period was from 15 July-18 August 2020, with a harvesting duration of 35 days and a flowering to harvesting duration of 105 days. During the off-season mangosteen production period, the flowering period occurred during 1-30 October 2020 and fruits were harvested from 1-25 February 2021, with a harvesting duration of 25 days and a flowering to harvesting duration of 123 days. In the on-season mangosteen production period, the number of flowers per branch, number of fruits per branch, circumference of fruits, and fruit weight were higher than in the off-season mangosteen production period; however, the number of edible pulp segments, peel thickness, percentage of translucent flesh, and percentage of fruit gumming were lower in the on-season than in the off-season mangosteen production period (Figures 3-a to 3-h). There were no differences in the percentage of fruit scars between the on- and off-season mangosteen production periods (Figure 3-i).

3-2- Weather Data in the Mangosteen Orchard

The average (±SD) monthly rainfall was 152.18±123.91 mm with an annual rainfall of 1,826.2 mm. The maximum and minimum monthly rainfall was observed in November 2020 and February 2021, respectively. The average (±SD) relative humidity and air temperature were 86.11±12.19% and 26.88±3.4°C, respectively.

3-3- Soil Temperature and Moisture at Four Depth Levels

Comparing soil temperature at the four depth levels, the soil temperature was highest at the 120 cm depth (15 cm depth: 26.47±1.22°C; 45 cm depth: 26.64±0.73°C; 90 cm depth: 26.62±0.59°C; 120 cm depth: 26.71±0.56°C; one-way ANOVA with Bonferroni posthoc tests: $F_{3,135472} = 47.252$, $P < 0.001$). Comparing soil moisture at the four depth levels, the soil moisture was the driest at a depth of 15 cm depth (49.91±60.10 cb), followed by 45 cm (38.67±44.78 cb), 120 cm (35.76±33.98 cb), and 90 cm (2.93±2.28 cb) (one-way ANOVA with Bonferroni post hoc tests: $F_{3,135472} = 6351.083$, $P < 0.001$). Leaf wetness at 160 cm above ground (4.34±6.46) was higher than that at 15 cm above ground (3.29±5.60) (t-test: $t_{66273.307} = -20.080$, $P < 0.001$).

3-4- Dry Periods in the On- and Off-Season Mangosteen Production Periods

Comparing the dry periods between the on- and off-season mangosteen production periods, there was lower relative humidity, soil moisture at 120 cm depth, and leaf wet-ness at 15 cm above ground during the off-season mangosteen production period; however, there was higher air temperature, soil moisture, and soil temperature at all four depth levels during the off-season than the on-season mangosteen production period (*t*-test: relative humidity: $t_{4648.053} = 3.006$, $P < 0.001$; soil moisture at 120 cm depth: $t_{1381} = 62.859$, $P < 0.001$; leaf wetness: $t_{4173} = 2.451$, $P < 0.05$; air temperature: $t_{4604.443} = -7.847$, $P < 0.001$; soil moisture at 15 cm depth: $t_{4793.613} = -64.076$, $P < 0.001$, 45 cm depth: $t_{4794} = -63.265$, $P < 0.001$, 90 cm depth: $t_{4280.013} = -305.264$, $P < 0.001$; soil temperature at 15 cm depth: $t_{2661.017} = -49.148$, $P < 0.001$, 45 cm depth: $t_{4794} = -60.265$, $P < 0.001$, 90 cm depth: $t_{4280.013} = -98.038$, $P < 0.001$, 120 cm depth: $t_{2447.316} = -95.391$, $P < 0.001$; Table 1). There was no difference in the amount of daily rainfall and leaf wetness at 160 cm above the ground between the on- and off-season mangosteen production periods (*t*-test: daily rainfall: $t_{47} = -0.086$, ns; leaf wetness: $t_{3293.212} = -1.817$, ns; Table 1).

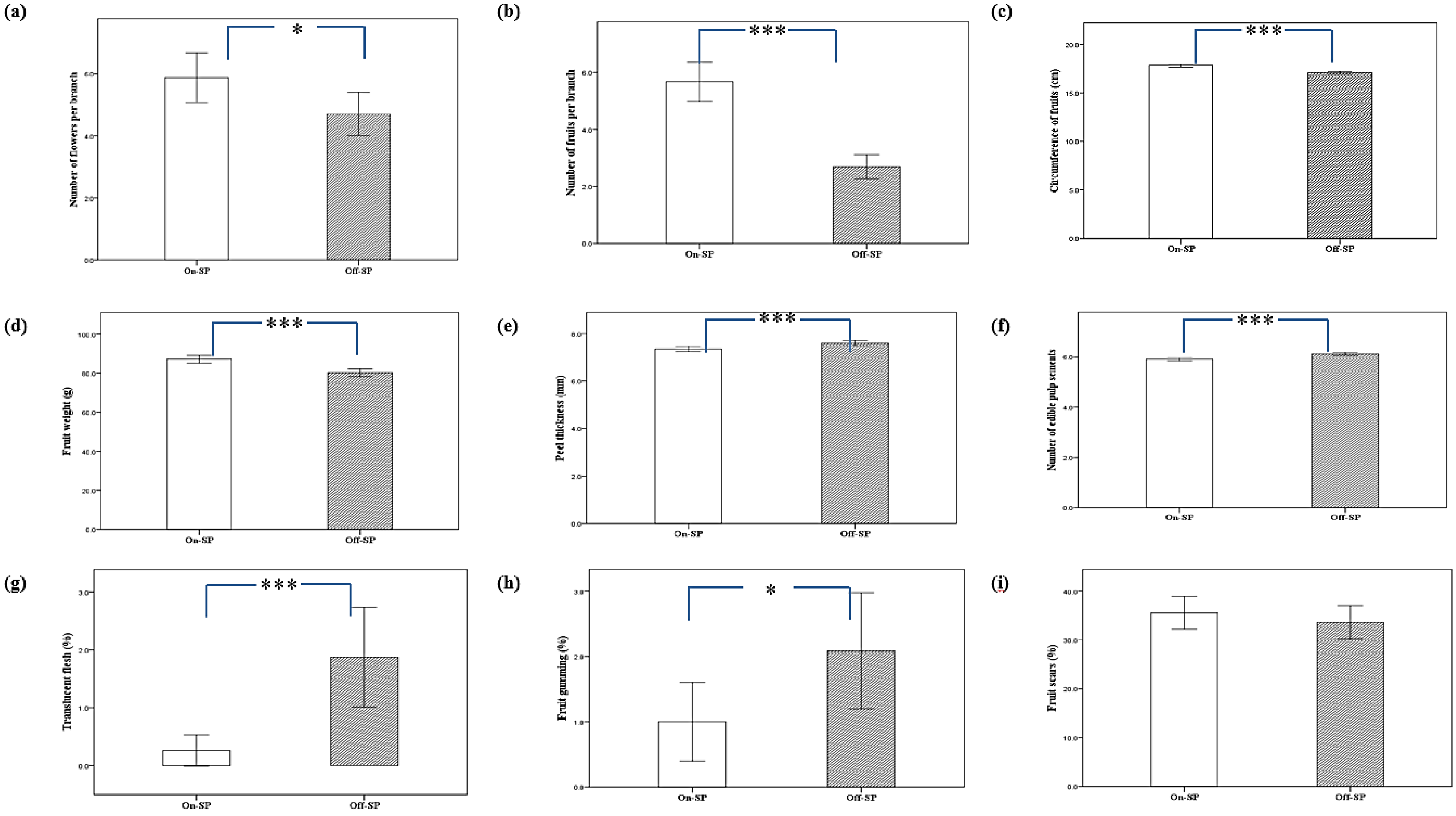

Figure 3. Mangosteen parameters in the on-season and off-season mangosteen production periods. (a) Number of flowers per branch, (b) Number of fruits per branch, (c) Circumference of fruits (cm) (d) Number of edible pulp segments, (e) Fruit weight (g), (f) Peel thickness (mm), (g) Translucent flesh (%), (h) Fruit gumming (%) and (i) Fruit scar (%). (*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$)

Table 1. Climatic and soil factors between the dry and flowering periods of the on-season and off-season mangosteen production periods (*P < 0.05, **P < 0.001)

Parameters	On-season mangosteen production period			Off-season mangosteen production period		
	Dry period	Flowering period	*t*-test	Dry period	Flowering period	*t*-test
Air temperature (°C)	27.05 ± 4.057	27.53 ± 4.08	$t_{4590.830}$ = -4.018**	27.92 ± 3.58	26.33 ± 3.02	$t_{4851.991}$ = 16.918**
Daily rainfall (mm)	0.809 ± 2.205	3.346 ± 13.494	t_{47} = -0.89	0.869 ± 2.666	7.608 ± 13.26	$t_{25.865}$ = -2.493*
Relative humidity (%)	81.60 ± 14.55	83.53 ± 13.74	t_{4606} = -4.633**	80.39 ± 13.16	90.65 ± 9.56	$t_{4557.843}$ = -31.488**
Soil temperature at 15 cm depth (°C)	26.01 ± 0.84	27.20 ± 1.26	$t_{4006.802}$ = -37.931**	26.90 ± 0.25	25.66 ± 1.019	$t_{2782.048}$ = 59.171**
45 cm depth (°C)	26.12 ± 0.37	27.06 ± 0.53	$t_{4113.241}$ = -70.537**	26.73 ± 0.34	26.09 ± 0.92	$t_{3143.592}$ = 32.731**
90 cm depth (°C)	26.13 ± 0.329	26.95 ± 0.347	$t_{4590.045}$ = -82.180**	26.96 ± 0.25	26.19 ± 0.94	$t_{2845.231}$ = 39.454**
120 cm depth (°C)	26.26 ± 0.266	27.03 ± 0.292	$t_{3020.705}$ = -69.304**	27.07 ± 0.22	26.46 ± 0.96	$t_{2760.075}$ = 30.616**
Soil moisture at 15 cm depth (cb)	82.38 ± 40.66	40.73 ± 29.41	$t_{4192.509}$ = 39.758**	160.43 ± 43.70	0.87 ± 1.72	$t_{2501.686}$ = 182.267**
45 cm depth (cb)	44.49 ± 23.31	35.43 ± 15.46	$t_{3997.353}$ = 15.496**	88.00 ± 24.24	1.04 ± 0.23	$t_{2494.443}$ = 179.184**
90 cm depth (cb)	0.00 ± 0.00	2.43 ± 1.22	t_{2302} = -95.534**	23.02 ±3.77	4.75 ± 1.39	$t_{3158.318}$ = 227.373**
120 cm depth (cb)	24.81 ± 14.68	39.55 ± 6.420	$t_{1771.581}$ = -34.967**	0.00 ± 0.00	1.33 ± 7.59	t_{2495} = -8.789**
Leaf wetness at 15 cm above ground	1.77 ± 4.744	9.07 ± 7.073	$t_{3955.334}$ = -38.941**	1.42 ± 4.19	5.22 ± 6.09	$t_{4636.595}$ = -21.950**
160 cm above ground	1.61± 4.596	1.65 ± 3.968	$t_{3086.612}$ = 2.265*	1.87 ± 4.581	6.99 ± 7.05	$t_{4064.937}$ = -33.954**

3-5- Dry and Flowering Periods in the On- and Off-Season Mangosteen Production Periods

Comparing the dry periods between the on- and off-season mangosteen production periods, there was lower relative humidity, soil moisture at 120 cm depth, and leaf wet-ness at 15 cm above ground during the off-season mangosteen production period; however, there was higher air temperature, soil moisture, and soil temperature at all four depth levels during the off-season than the on-season mangosteen production period (t-test: relative humidity: $t_{4648.053}$ = 3.006, P < 0.001; soil moisture at 120 cm depth: t_{1381} = 62.859, P < 0.001; leaf wetness: t_{4173} = 2.451, P < 0.05; air temperature: $t_{4604.443}$ = -7.847, P < 0.001; soil moisture at 15 cm depth: $t_{4793.613}$ = -64.076, P < 0.001, 45 cm depth: t_{4794} = -63.265, P < 0.001, 90 cm depth: $t_{4280.013}$ = -305.264, P < 0.001; soil temperature at 15 cm depth: $t_{2661.017}$ = -49.148, P < 0.001, 45 cm depth: t_{4794} = -60.265, P < 0.001, 90 cm depth: $t_{4280.013}$ = -98.038, P < 0.001, 120 cm depth: $t_{2447.316}$ = -95.391, P < 0.001; Table 1). There was no difference in the amount of daily rainfall and leaf wetness at 160 cm above the ground between the on- and off-season mangosteen production periods (*t*-test: daily rainfall: t_{47} = -0.086, ns; leaf wetness: $t_{3293.212}$ = -1.817, ns; Table 1).

3-5-1- On-Season Mangosteen Production Period

During the dry period, there was lower relative humidity, air temperature, soil moisture at the 90 and 120 cm depths, soil temperature at all four depth levels, and leaf wetness at both levels; however, there was higher soil moisture at the 15 and 45 cm depths than during the flowering period (Table 1). No differences were observed in the amount of daily rainfall.

3-5-2- Off-Season Mangosteen Production Period

During the dry period, there was a lower amount of daily rainfall, relative humidity, soil moisture at 120 cm depth, and leaf wetness at both levels. However, there was a higher air temperature, soil moisture at 15, 45, and 90 cm depth, and soil temperature at all four depth levels than during the flowering period (Table 1).

4- Discussion

4-1- Fruit Quality between the On- and Off-Season Mangosteen Production Periods

Our results showed that mangosteen fruits in both the on- and off-season production periods had similar fruit sizes, peel thickness, and number of edible pulp segments, as in previous studies. Previous studies have reported that mangosteens have an average fruit weight of 75-150 g, fruit circumference of 15.95-23.92 cm, peel thickness of 6-10 mm, and the number of edible pulp segments of 4-8 segments. Fruit weight varies depending on the age of the tree (i.e., younger trees produce a smaller fruit size than older trees) and its geographical location (e.g., mangosteens from the south of the Philippines are larger than those of the Malay Peninsula) [2, 29].

Many studies have reported that off-season mangosteens can be produced by the induction of off-season flowering with a dry period of 15-30 days [2, 3, 5, 17-19, 32]. Drought-inducing flowering with the involvement of inhibitor hormones is essential for floral initiation. Adequate water supply during floral maturation is required for good growth [3]. Our results showed that fruit development that occurred during off-season flowering occurred under suboptimal growth conditions. This can lead to poor fruit set, poor fruit development, and severe cracking. Previous studies have reported low-quality off-season flowering in longan (*Dimocarpus longan* Lour.) [33, 34], and lychee (*Litchi chinensis* Sonn.) [33, 35-37] due to weather-inducing stress, such as cold, dry, or abrupt temperature fluctuations, during the early stage of fruit development. This resulted in reduced fruit growth potential, excessive fruit drop, severe cracking, and off-season fruit periods. In addition, mangosteen may have high productivity during the on-season production period, which may result in low photosynthesis, causing low assimilation and affecting the source-sink relationship during the off-season production period [38]. An inadequate supply of photosynthesis can cause low total sugar content of leaves on shoots, leading to high flower and young fruit shedding with small fruit sizes [39].

The major problems limiting the marketable yield of mangosteen in Thailand are translucent flesh disorder and gamboge disorder [21]. Our results showed that translucent flesh disorder and gamboge disorder during off-season fruiting were higher than those during on-season fruiting. Apiratikorn et al. [5] also reported that translucent flesh disorder during off-season mangosteen fruiting was higher than that during on-season fruiting in Phathalung Province, Southern Thailand. Severe cracking of mangosteen fruits can cause translucent flesh and gamboge disorders. Fruit cracking occurs when the aril expands rapidly, causing a sudden increase in internal stress, which results in pericarp breakdown [40]. In this study, the off-season mangosteen trees began flowering in October and early fruit development was exposed to drought in December, while aril growth in later stages occurred at much warmer and drier temperatures in January-early February. Compared to the on-season fruits, the off-season fruits had a less developed pericarp, which was reflected by the significantly reduced fresh weight and fruit size. However, the number of seeds, which was reflected by the significant increase in the number of edible pulp segments, was higher than that in on-season mangosteens. This suggests that mangosteen trees are preferentially mobilized to satisfy seed development.

The three main factors that can trigger flower development in mangosteens are water stress duration, apical bud age, and plant vigor [41]. Our results showed that off-season mangosteen trees had a lower number of flowers and fruits per branch than on-season mangosteen trees. Suboptimal conditions during off-season mangosteen production may lead to water stress, causing breakage of mangosteen latex vessels and latex glands throughout the tree (i.e., flowers, leaves, and branches). Breakage of latex vessels and glands at the shoot apex leads to a lower number of flowers and fruits per branch [3]. This indicated that off-season mangosteen trees had more limited resources for fruit growth, which resulted in smaller fruit size, lower blossoms, and higher fruit drop.

4-2- Climatic Factors between the On- and Off-Season Mangosteen Production Periods

Our results showed that the dry period of the on-season mangosteen production period occurred from 1–24 March 2020 (25 days) and the dry period of the off-season mangosteen production period occurred from 20 August–14 September 2020 (26 days). Our results support those of previous studies showing that mangosteen trees under natural conditions require a short dry season (15–30 days) to stimulate flowering, followed by irrigation or rainfall [2, 3, 5, 18, 19]. Apiratikorn et al. [5] studied mangosteens in southern Thailand and reported that a drought period of 21 days induced mangosteen flowering in Phathalung Province. We studied a mangosteen orchard located in Nakhon Si Thammarat Province, which borders Phathalung Province, and obtained similar findings (i.e., 25–26 days of dry period before flowering). Salakpetch et al. [3] reported that mangosteen orchards located in Chantaburi Province, eastern Thailand, had a drought period ranging from 7 to 25 days to induce mangosteen flowering. Under severe water stress conditions, floral buds emerged 25 days after irrigation with a large amount of water to rehydrate the buds and resume growth and development.

Bourdeaut & Moreuil [42] reported that the ideal relative humidity for mangosteen orchards is 80% or higher. Our results showed that the average relative humidity ranged between 80.39-90.65%, which was greater than 80%. In addition, our results showed that during the on-season production period, the fluctuation between the maximum and minimum relative humidity was wider than that during the off-season mangosteen production period. Kennedy et al. [43] reported that a high relative humidity of 90% may be responsible for the conversion of residual food reserves into flower primordia in mango trees.

In Southeast Asia, mangosteen production varies depending on the amount of annual rainfall in different geographical locations and seasons. Mangosteens require well-distributed annual rainfall exceeding 1,270 mm with ten consecutive wet months [2, 32, 44–46]. Excessive rainfall during flowering prevents fruit setting and favors the development of pests and diseases [17, 47, 48]. The distribution patterns of rain had a direct effect on the flowering of mangosteen trees. Factors affecting the flowering period include a decrease in rainfall by approximately 1-2 months before flowering because the mangosteens' dormancy occurs during the dry season to absorb the accumulation needed for flowering and fruiting [49]. Mangosteen trees are water-resistant but not drought-resistant; therefore, water deficit stress should be avoided, and watering is necessary during the dry period. The percentage of soil moisture during the off-season production period was also drier during the off-season because of low rainfall. Naik [50] reported that the dry period helped the shoot obtain the desired rest period for the successful initiation of flower buds. Regarding the direct effect of cloudy weather and excessive rainfall during the flowering period, Singh reported that these factors lead to favorable conditions for pests and diseases that damage the crop. Mango trees require a dry period for flower bud formation, and flowering occurs naturally after dry and cool seasons [51].

Our results showed that the maximum air temperature in the off-season mangosteen production period during 2020 ranged from 28.5–36.2 °C. These temperature regimes were probably conducive to flowering and fruit setting during the off-season production period. Mangosteens thrive best in the temperature range of 25–35 °C [42, 46], but a temperature range of 15-20 °C results in slow growth and is not recommended for planting mangosteen trees.

4-3- Soil Temperature and Moisture at Four Depth Levels

Many studies have reported that drought can induce flowering in several plant species, including durian [10, 11], mango [15], citrus fruits [9], longan [13], lime [12], loguat [14], and mangosteen [17]. A drought period lowers soil moisture and increases soil temperature. Our results showed that the fluctuation between the maximum and minimum soil moisture was widest at a depth of 15 cm. Sdoodee et al. [49] studied soil moisture in a mangosteen orchard at six depths (10, 20, 30, 40, 60, and 100 cm) and reported similar findings, where the soil moisture at a depth of 10–40 cm showed the highest variability, but at depths of 60 and 100 cm, the soil moisture content had the lowest variability. This high fluctuation could be because the soil at a depth of 15 cm was the topsoil, which was directly affected by air temperature, sunlight, wind, and high respiration from living organisms, including earthworms, plant roots, fungi, and bacteria.

Similar to the findings of Singh et al. [52], our results showed that soil temperature increased as depth increased. Soil temperature is strongly influenced by ambient temperature, which has a strong effect on the vegetative and reproductive growth of mangoes [53]. These results indicate that environmental control over shoot growth of mango trees may, in part, be related to soil temperature.

5- Conclusion

Thailand is the leading mangosteen producer and exporter, shipping to Taiwan, Hong Kong, Japan, China, the US, and Canada. Climate-related factors affect mangosteen flowering and fruit quality during the on- and off-season production periods. For the on-season period, the flowering period occurred from 1–30 April 2020, and the harvesting period was from 15 July to 18 August 2020, with a harvesting duration of 35 days and a flowering-to-harvesting duration of 105 days. For the off-season period, the flowering period occurred from 1-30 October 2020, and the fruits were harvested during 1-25 February 2021, with a harvesting duration of 25 days and a flowering to harvesting duration of 123 days. In the on-season mangosteen production period, the number of flowers per branch, number of fruits per branch, circumference of fruits, and fruit weight were higher than those in the off-season mangosteen production period. However, the number of edible pulp segments, peel thickness, percentage of translucent flesh, and percentage of fruit gumming were lower during the on-season than during the off-season mangosteen production period. No differences were observed in the percentage of fruit scars between the on- and off-season mangosteen production periods. During the off-season mangosteen production period, there was lower relative humidity, soil moisture at 120 cm depth, and leaf wetness at 15 cm above ground; however, there was higher air temperature, soil moisture, and soil temperature at all four depth levels when compared to the on-season mangosteen production period.

6- Declarations

6-1- Author Contributions

Conceptualization, K.J.; methodology, K.J., P.B., and M.J.; formal analysis, K.J. and P.B.; investigation, K.J.; data curation, P.B.; writing—original draft preparation, K.J. and P.B.; writing—review and editing, K.J., P.B., and M.J.; project administration, K.J.; funding acquisition, K.J. All authors have read and agreed to the published version of the manuscript.

6-2- Data Availability Statement

The data presented in this study are available on request from the corresponding author. Due to confidentiality agreements, supporting data can only be made available to bona fide researchers subject to a non-disclosure agreement. Details of the data and how to request access are available from Assoc. Prof. Dr. Krisanadej Jaroensutasinee, PI at Center of Excellence for Ecoinformatics, Walailak University, Thailand.

6-3- Funding

This research was funded in part by the Office of Higher Education Commission, National Science Technology and Innovation Policy Office under Talent Mobility Project, grant number SCH021, and the Centre of Excellence for Ecoinformatics, Walailak University.

6-4- Acknowledgements

We would also like to thank two reviewers for providing suggestions on previous versions of this manuscript and David C. Chang, and Mark Treve for providing English language and editing support through their comments on previous versions of this work.

6-5- Institutional Review Board Statement

Not applicable.

6-6- Informed Consent Statement

Not applicable.

6-7- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

7- References

[1] Agricultural Import-Export Mangosteen Production. (2020). Office of Agricultural Economics, Ministry of Agriculture and Cooperative, Bangkok, Thailand. (In Thai).

[2] Othman, Y., & Tindall, H. D. (2016). Mangosteen cultivation: Series FAO Plant Production and Protection Paper, 129. doi:10.5962/bhl.title.121365.

[3] Salakpetch, S., Poonnachit, U., & Horticultural, C. (2006). Soil Moisture Stress and Irrigation Management Promote Mangosteen. Journal of Hawaiian and Pacific Agriculture, 13(1), 35-41.

[4] Uraipan P. (2009). The impact of climate changes on phenology of Longkong (Lansium domesticum Corr.). Master Thesis, Prince of Songkla University, Songkla, Thailand.

[5] Apiratikorn, S., Sdoodee, S., Lerslerwong, L., & Rongsawat, S. (2012). The impact of climatic variability on phenological change, yield and fruit quality of mangosteen in Phatthalung province, Southern Thailand. Agriculture and Natural Resources, 46(1), 1-9.

[6] Apiratikorn, S., Sdoodee, S., & Limsakul, A. (2014). Climate-related changes in tropical-fruit flowering phases in Songkhla province, Southern Thailand. Research Journal of Applied Sciences, Engineering and Technology, 7(15), 3150–3158. doi:10.19026/rjaset.7.654.

[7] Ounlert, P., & Sdoodee, S. (2015). The Effects of Climatic Variability on Mangosteen Flowering Date in Southern and Eastern of Thailand. Research Journal of Applied Sciences, Engineering and Technology, 11(6), 617–622. doi:10.19026/rjaset.11.2021.

[8] Ounlert, P., Sdoodee, S., & Tongkhow, P. (2017). The mangosteen flowering date model in Nakhon Si Thammarat Province, Southern Thailand. Journal of Central European Agriculture, 18(1), 176–184. doi:10.5513/JCEA01/18.1.1876.

[9] Khan, F. S., Gan, Z. M., Li, E. Q., Ren, M. K., Hu, C. G., & Zhang, J. Z. (2022). Transcriptomic and physiological analysis reveals interplay between salicylic acid and drought stress in citrus tree floral initiation. Planta, 255(1), 24. doi:10.1007/s00425-021-03801-2.

[10] Safari, S., Athirah, N., Jamaludin, J., Sunthralingam, C., & Mustaffa, R. (2018). Durian as new source of Malaysia's agricultural wealth. FFTC Agricultural Policy Platform (FFTC-AP), Taipei, Taiwan R.O.C.

[11] Ketsa, S., Wisutiamonkul, A., Palapol, Y., & Paull, R. E. (2020). The durian: Botany, horticulture, and utilization. Horticultural reviews, 125-211, John Wiley & Sons, New York, United States. doi:10.1002/9781119625407.ch4.

[12] Ariza-Flores, R., Michel-Aceves, A. C., Gálvez-Marroquín, L. A., Trujillo-García, D., Avendaño Arrazate, C. H., & Espinosa-Paz, N. (2021). Effects of flowering and production inducers in the Mexican lime (Citrus Aurantifolia Swingle). Agro Productividad, 13(12), 19–24. doi:10.32854/agrop.v13i12.1737.

[13] Jue, D., Sang, X., Liu, L., Shu, B., Wang, Y., Liu, C., Wang, Y., Xie, J., & Shi, S. (2019). Comprehensive analysis of the longan transcriptome reveals distinct regulatory programs during the floral transition. BMC Genomics, 20(1), 126. doi:10.1186/s12864-019-5461-3.

[14] Chi, Z., Wang, Y., Deng, Q., Zhang, H., Pan, C., & Yang, Z. (2020). Endogenous phytohormones and the expression of flowering genes synergistically induce flowering in loquat. Journal of Integrative Agriculture, 19(9), 2247–2256. doi:10.1016/s2095-3119(20)63246-4.

[15] Prates, A. R., Züge, P. G. U., Leonel, S., Souza, J. M. A., & De Ávila, J. (2021). Flowering induction in mango tree: Updates, perspectives and options for organic agriculture. Pesquisa Agropecuaria Tropical, 51, 68175. doi:10.1590/1983-40632021v5168175.

[16] Then, K. H., Norshafiqah, K., & Muhammad Faiz, O. (2019). The Effect of Paclobutrazol in Improving the Yield Performance of Mangosteen (Garcinia mangostana). International Journal of Agriculture Innovations and Research, 8(3), 1473–2319.

[17] Boonklong O., Jaroensutasinee M., & Jaroensutasinee K. (2006). Climate change affecting mangosteen production in Thailand. Proceedings of the 5th WSEAS International Conference on Environmental, Ecosystems and Development, 20-22 November, 2006, Venice, Italy.

[18] Chutinunthakun T. (2001). Prevention of the incidence of translucent flesh disorder and internal gumming fruits in mangosteen (Garcinia mangostana Linn.) and screening techniques. Master Thesis, Prince of Songkla University, Songkhla, Thailand.

[19] Sdoodee, S., & Chiarawipa, R. (2005). Regulating irrigation during pre-harvest to avoid the incidence of translucent flesh disorder and gamboge disorder of mangosteen fruits. Songklanakarin Journal of Science Technology, 27(5), 957–965.

[20] Wang, Z., & Stutte, G. W. (2019). The Role of Carbohydrates in Active Osmotic Adjustment in Apple under Water Stress. Journal of the American Society for Horticultural Science, 117(5), 816–823. doi:10.21273/jashs.117.5.816.

[21] Pechkeo, S., Sdoodee, S., & Nilnond, C. (2007). Changes of Plant nutrients concentration in soils and trees of mangosteen (Garcinia mangostana L.) during the fruit development. Agriculture and Natural Resources, 41(1), 61-71.

[22] Salakpetch S. (2000). Mangosteen production in Thailand. Proceedings of the 10th Annual International Tropical Fruit Conference, 20-22 October, 2000, Hawaii, USA.

[23] Campbell, C. W. (1966). Growing the Mangosteen in Southern Florida. Florida State Horticultural Society, 79(2525), 399–401.

[24] Almeyda N., & Martin F. W. (1978). Tropical fruits: The Mangosteen. World Farming 20(8), 20-23.

[25] Galang, F. G. (1955). Fruit and nut growing in the Philippines. Araneta Institute of Agriculture, Bulacan, Philippines.

[26] Nilnond, C., Jatupote, W., Leowarin, W., & Yong, S. (1995). Chemical fertility status of some growing mangosteen soils in southern Thailand. Warasan Songkhlanakharin, 17(4), 381-393. (In Thai).

[27] Verheij E. W. M. (1992). Garcinia mangostana. Edible Fruits and Nuts, Prosea 2, 175-181, Bogor, Indonesia.

[28] Nagy S., & Shaw P. (1980). Tropical and Subtropical Fruits: Composition, Properties and Uses. AVI Publishing, Westport, United States.

[29] Ratnadass, A., & Martin, T. (2022). Crop protection practices and risks associated with infectious tropical parasitic diseases. Science of the Total Environment, 153633. doi:10.1016/j.scitotenv.2022.153633.

[30] Krishnamurthi, S., & Rao, N. M. (1962). Mangosteen deserves wider attention. Indian Hort, 7(1), 3-8.

[31] Malip, M., & Masri, M. (2006). Establishment of protocol for carbohydrate analysis and monitoring seasonal variations between carbohydrates and nitrogen levels in Garcinia mangostana (mangosteen). Acta Horticulturae, 727, 569–575. doi:10.17660/actahortic.2006.727.71.

[32] Luo, M., Sa, C., Meng, F., Duan, Y., Liu, T., & Bao, Y. (2020). Assessing extreme climatic changes on a monthly scale and their implications for vegetation in Central Asia. Journal of Cleaner Production, 271, 122396. doi:10.1016/j.jclepro.2020.122396.

[33] Huang, X. (2005). Fruit disorders. Litchi and Longan: Botany, Production, and Uses. CABI Publishing, Wallingford, United Kingdom.

[34] Yang, W. H., Deng, S. C., Zhu, X. C., Wang, H. C., Wu, H., & Huang, X. M. (2010). Developmental problems in over-winter off-season longan fruit. II: Development of pericarp structure. Scientia Horticulturae, 126(3), 359–365. doi:10.1016/j.scienta.2010.07.029.

[35] Joubert A. J. (1970). The Litchi. Governmental Printer, Pretoria, South Africa.

[36] Kanwar, J. S., & Nijjar, G. S. (1982). Fruit growth in relation to cracking in Litchi (Litchi Chinensis Sonn) Cv.'Hongkong'. Haryana Journal of Horticultural Sciences (India), 1-11.

[37] Menzel, C. M., Oosthuizen, J. H., Roe, D. J., & Doogan, V. J. (1995). Water deficits at anthesis reduce CO2 assimilation and yield of lychee (Litchi chinensis Sonn.) trees. Tree Physiology, 15(9), 611–617. doi:10.1093/treephys/15.9.611.

[38] Weibel J. (1993). Physiology and Growth of Mangosteen (Garcinia mangostana L.) Seedlings. Dissertation of Doctor Scientarium Agrariarum. Universität Berlin, Berlin, Germany.

[39] Sdoodee, S., Phonrong, K., & Ruongying, Y. (2008). Mangosteen crop load affects physiological responses, fruit yield and fruit quality. Acta Horticulturae, 773, 187–194. doi:10.17660/ActaHortic.2008.773.27.

[40] Li, J., Huang, H., Gao, F., Huang, X., & Wang, H. (2001). An overview of litchi fruit cracking. Acta Horticulturae, 558, 205–208. doi:10.17660/ActaHortic.2001.558.28.

[41] Poonnachit, U., Salakpetch, S., Chandraparnik, S., & Hiranpradit, H. (1996). Phenological development and plant vigour affected mangosteen production. Proceedings of the International Conference on Tropical Fruits, 23-26 July, Kuala Lumpur, Malaysia.

[42] Bourdeaut, J., & Moreuil, C. (1970). Le Mangoustanier. Ses possibilités de culture en Côte d'Ivoire et à Madagascar. Fruits, 25(4), 223-245. (In French).

[43] Kennedy R. R., Swaminathan C., Amutha S., Rajesh T., & Prem J. J. (2009). Off- season flowering in mango- a biological wonder in Kanyakumari district, India. National level training cum seminar on off-season mango production. Horticultural Research Station, Pechiparai, India.

[44] Firminger T. (1869). Manual of Gardening for Bengal and Upper India. Calcutta, India. doi:10.5962/bhl.title.29357.

[45] El-Kenawy, A. E. M., Hassan, S. M. A., & Osman, H. E. H. (2018). Mangosteen (Garcinia mangostana L.). In H. N. & D. Z (Eds.), Nonvitamin and Nonmineral Nutritional Supplements. UK, University of Southampton, International Centre for Underutilised Crops. doi:10.1016/B978-0-12-812491-8.00045-X.

[46] Hume, E. P., & Cobin, M. (1946). Relation of seed size to germination and early growth of mangosteen. Proceedings of the American Society for Horticultural Science (EUA), 48, 298-302.

[47] Gangolly, S. R., Singh, R., Katyal, S. L., & Singh, D. (1957). The mango. Indian Journal of Horticulture, 14(4), 246-249.

[48] Gandhi S. R. (1959). The Mango. Farm Bulletin, Indian Council of Agricultural Research, New Delhi, India.

[49] Sdoodee, S., Lerslerwong, L., & Rugkong, A. (2010). Effects of climatic condition on off-season mangosteen production in Phatthalung Province. Department of Plant Science, Faculty of Natural Resources, Prince of Songkla University, Songkla, Thailand.

[50] Naik K. C. (1949). South Indian fruits and their culture. P. Varadachary & Co., Madras, India.

[51] Rajan S. (2009). Off-season mango production: present status and future scope. In National level training cum seminar on off-season mango production. Horticultural Research Station, Pechiparai, India.

[52] Singh, C. D., Singh, R. C., Singh, K. P., & Singh, R. (2016). A Sensor Network for Monitoring Soil Moisture and Temperature of Wheat Crops under Permanent Raised bed in Vertisols. International Journal of Innovative Studies in Sciences and Engineering Technology, 2(9), 8–12.

[53] Yusof, I. M., Buchanan, D. W., & Gerber, J. F. (2022). The Response of Avocado and Mango to Soil Temperature1. Journal of the American Society for Horticultural Science, 94(6), 619–621. doi:10.21273/jashs.94.6.619.