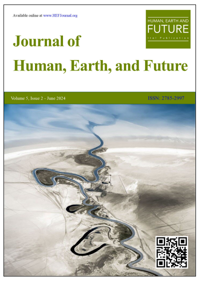
HUMAN, EARTH AND FUTURE
Ital Publication
ISSN: 2785-2997

Available online at www.HEFJournal.org

Journal of
Human, Earth, and Future

Vol. 5, No. 2, June, 2024



Mangosteen Yield and Fruit Quality under Regulated Irrigation with Sensors and IoT

Krisanadej Jaroensutasinee [1], Mullica Jaroensutasinee [1*], Piyatida Boonsanong [1], Elena Sparrow [2]

[1] Center of Excellence for Ecoinformatics, School of Science, Walailak University, Nakhon Si Thammarat 80161, Thailand.

[2] International Arctic Research Center, Department of Natural Resources and Environment, University of Alaska Fairbanks, AK, USA.

Received 26 January 2023; Revised 09 May 2024; Accepted 14 May 2024; Published 01 June 2024

Abstract

Mangosteen (*Garcinia mangostana* L.) generates over 88 billion USD in export revenue to Thailand annually but is restrained due to fruit defects. This study aimed to determine whether smart irrigation with sensors, IoT, and real-time data collection for regulating stable soil water content affects mangosteen fruit quantity and quality. Climate, soil, and mangosteen parameters were compared between irrigated and non-irrigated productions. Flowering and fruit yield data were collected from twenty randomly selected mangosteen trees per irrigation treatment. The results showed that air and soil temperatures were lower, but relative humidity and soil moisture on mangosteen production were greater in irrigated trees than in non-irrigated trees. Irrigated and non-irrigated mangosteen trees showed no significant difference in trunk diameter or crown size. Irrigation boosted mangosteen yields with increased flowers, fruits, and weight but thinner peels, fewer pulp segments, and a higher vulnerability to fruit imperfections. The mean fruit circumference did not differ significantly between non-irrigated and irrigated mangosteen production systems. Mangosteen fruits in irrigated production had fewer fruit defects than those in non-irrigated production. Regulated irrigated mangosteen production with stable soil moisture using soil moisture sensors and IoT produced high-quantity and quality mangosteens with fewer fruit defects.

Keywords: Irrigation; Fruit Quality; Mangosteen; Internet of Things (IoT).

1. Introduction

Increasing water use efficiency in irrigated agriculture with smart technologies like sensors and the Internet of Things (IoT) is a growing trend in agriculture [1]. Smart irrigation necessitates real-time data collection by integrating sensors and wireless sensor communication on the weather, soil, and plant parameters to augment plant growth and productivity, reducing environmental impacts and conserving resources [2]. Implementing soil moisture monitoring for irrigation scheduling allows for data-driven decision-making regarding irrigation water volume, leading to enhanced water use efficiency, improved soil moisture management, and potentially boosted plant productivity through optimized water supply to the root zone [3]. By tailoring irrigation applications to meet the actual plant water demand at different soil depths, farmers can minimize water waste and optimize resource utilization. Precision irrigation and optimized water allocation methods address key challenges in water-limited agroecosystems by reducing non-beneficial water losses through evapotranspiration and runoff and maximizing plant water uptake and utilization for enhanced biomass production [4].

* Corresponding author: mullica.jn@gmail.com; jmullica@wu.ac.th

http://dx.doi.org/10. 28991/HEF-2024-05-02-05

Within the complex matrix of environmental factors influencing agricultural output, limited water resources represent a crucial bottleneck due to their essential role in plant physiological processes and their vulnerability to climate variability and anthropogenic activities [5]. By leveraging real-time data and tailored irrigation strategies, advancements in precision irrigation allow for targeted water application, maximizing water productivity, and minimizing water use efficiency losses in resource-constrained agroecosystems, thus fostering sustainable food security [6]. A substantial body of research demonstrates a positive association between regulated irrigation and fruit yield and quality across various plant species. Studies have documented significant increases in yield and improvements in quality parameters (e.g., sugar content, firmness) under controlled irrigation regimes, e.g., African Rose plum (*Prunus salicina* L.) [6], citrus (*Citrus sinensis* L.) [7], Japanese plum (*Prunus salicina* Lindell 'Methly') [8], mango (*Magifera indica* L.) [9], olive [10], peach (*Prunus persica* L.) [11], bell pepper (*Capsicum annuum* L.) [12], and tomato (*Solanum lycopersicum* Mill.) [13].

The mangosteen (*Garcinia mangostana* L.) drives over 540–560 million US dollars, representing a 14.6–18.8% growth in Thailand's export revenue to China due to its prime location to be able to ship fresh, high-quality mangosteen to China [14]. Fruit defects are undoubtedly a significant roadblock, but other factors like inconsistent yields, inadequate postharvest handling, and limited cold storage facilities also contribute to the constrained export growth of mangosteens. Addressing these multifaceted challenges is crucial to unlocking the full potential of this tropical treasure in the global market. The critical mangosteen defects that reduce export fruit quality are translucent flesh, small fruit size, and fruit gumming [15–17]. Understanding the role of environmental water stress in promoting cuticular fracture is crucial for developing mitigation strategies, such as optimized irrigation regimes or cultivar selection based on cuticle resilience, to minimize fruit defects and improve crop resilience in regions with pronounced seasonal variations in water availability [18–19]. The surplus of soil moisture during the wet season can cause extreme fluctuations in soil water and affect the turgor pressure, causing yellow latex tubes to burst and contaminate the mangosteen fruits [20]. This research examined whether smart irrigation with sensors, IoT, and real-time data collection for regulating stable soil water content affects mangosteen fruit quantity and quality by comparing irrigated and non-irrigated mangosteen production (Figure 1). Based on current literature and established physiological principles, we hypothesized that irrigated mangosteen production would exhibit increased floral and fruit set (flowers and fruits per branch), elevated fruit weight, and decreased fruit defects, the thickness of peel, and segments of edible pulp compared to non-irrigated production.

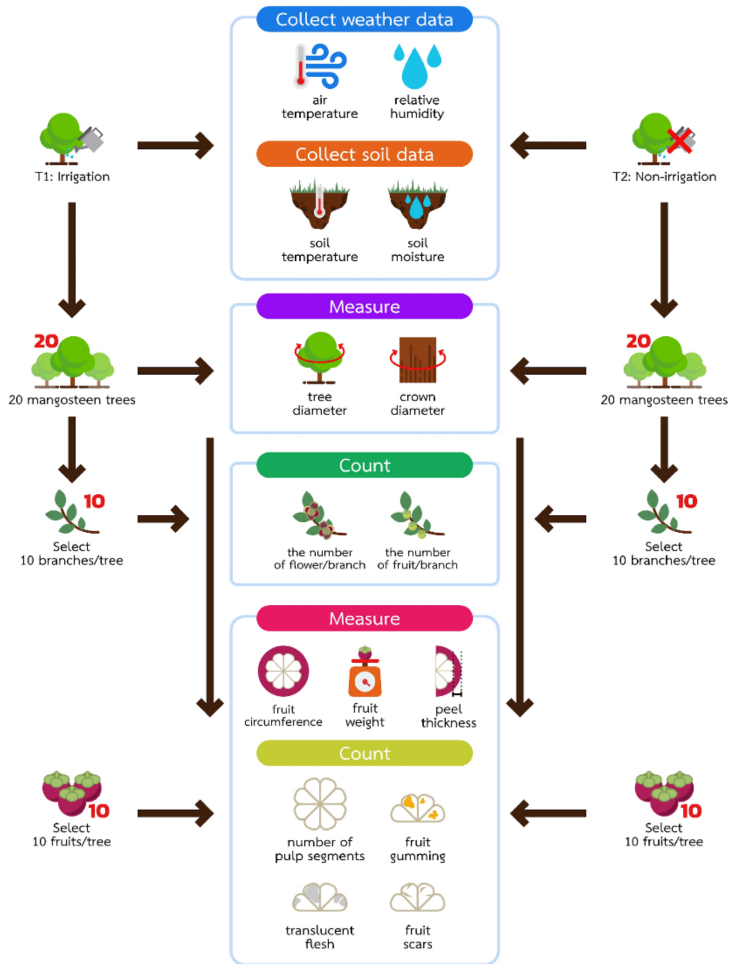
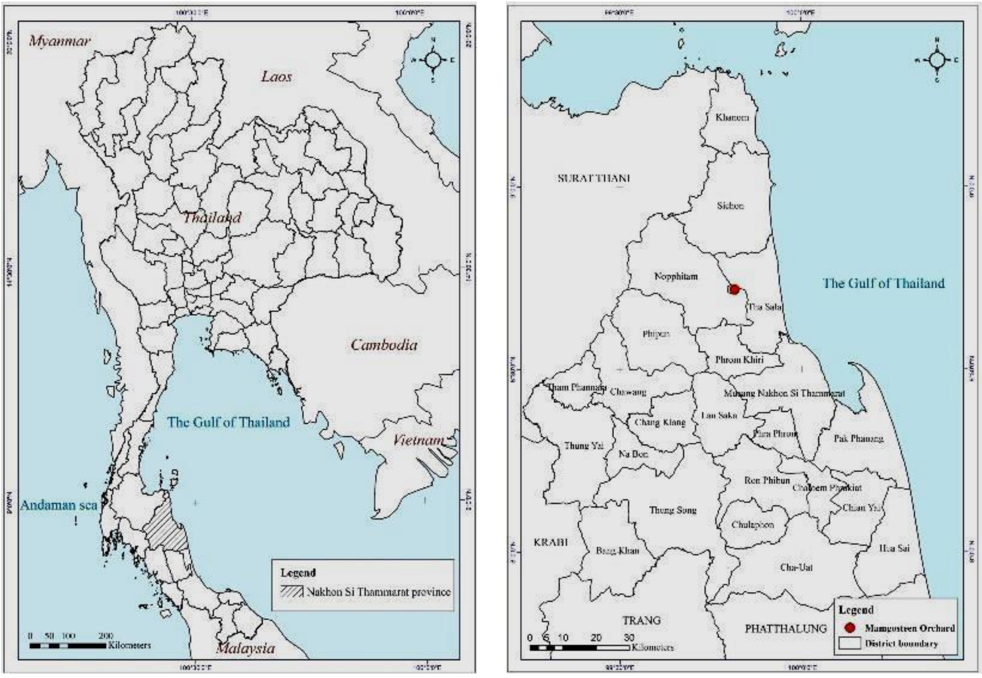


Figure 1. Experimental design and sampling strategy for evaluating mangosteen fruit quality under irrigated and non-irrigated conditions

2. Materials and Methods

2.1. Study Area

The study was conducted within a well-maintained mangosteen plantation situated in Nakhon Si Thammarat at 8°43′ N latitude and 99°49′ E longitude in Southern Thailand. This location is representative of soil and climatic conditions typical of commercial mangosteen production in the region. The 0.48-ha orchard boasts about 80 mango trees that are 20-25 years old (Figures 2).



(a) (b)

Figure 2. (a) Thailand map and (b) Mangosteen orchard location map: detailed view within Nakhon Si Thammarat

2.2. Mangosteen Biology

In Southeast Asia, particularly Thailand, mangosteen cultivation is a crucial fruit production source, significantly contributing to global food security and regional agricultural economies [21]. With a colossal planting area of 67,151 hectares and an annual yield of 340,000 tons, Thailand stands unchallenged as the world's top mangosteen supplier, with China receiving most of its exports. [22]. Mangosteen is a perennial plant with a dark brown bark that produces purple-red skin fruit with edible white, soft, juicy, sweet, and acidic pulp [23]. Mangosteen grows at 20°C, with susceptibility to sunburn increasing significantly above 38–40°C [24].

2.3. Data Collection

NB-IoT-enabled weather stations were strategically placed at a standardized height of 1.5 m above the ground surface, following World Meteorological Organization (WMO) recommendations for accurate air temperature and humidity measurements. Soil temperature and moisture sensors were installed concurrently at 15 cm depth within the root zone to monitor soil moisture and temperature fluctuations. Meteorological and soil data were acquired online at ten-minute intervals, enabling continuous and high-resolution monitoring of environmental conditions. Soil moisture sensors were electrodes placed into the soil to measure soil moisture from 0 centibar or cb (saturated soil) to 1,024 cb (dried soil). A comparative study assessed climatic and soil factors, along with mangosteen growth and fruit quality parameters, across two distinct mangosteen production sites: (1) irrigated and (2) non-irrigated production sites. Weather and soil data were further delivered to the Magellan cloud to view the data and graphs.

As key indicators of tree growth and resource acquisition, DBH and crown width were assessed in 20 randomly selected individuals per treatment, providing quantitative data for further analysis of treatment effects. Ten branches were randomly selected from each of the 20 randomly chosen trees (totaling 200 branches), resulting in a final sample size of 200. Quantitative data were collected on floral and fruit development in irrigated and non-irrigated production systems. Floral and fruit development data included the number of flowers per branch, flowering duration, harvesting periods, and harvesting duration; ten mature fruits were randomly selected per tree (200 totals per site) for subsequent measurements. We sampled ten fruits per tree for fruit quality, with 200 fruits in irrigated and 200 in non-irrigated productions. Each fruit was weighed and measured for circumference. At the optimal edible ripening stage, fruits were harvested and subjected to destructive analysis. Peel thickness was precisely measured using a calibrated digital caliper, and pulp segments were meticulously counted and recorded.

This study employed visual inspection to evaluate fruit quality parameters, specifically recording the percentage of individual fruits exhibiting gumming, translucent flesh, and scarring within irrigated and non-irrigated treatment groups. Our study categorized fruit damage as none (0%), minor (1-25%), or moderate (26-50%). Notably, no fruit exhibited severe damage exceeding 50%.

2.4. Data Analysis

When the data satisfies the necessary assumptions. Statistical differentiation of climatic, soil, and mangosteen parameters between irrigated and non-irrigated production systems was achieved using independent-sample t-tests with adjusted degrees of freedom. The Chi-squared tests determined the differences in the number of fruits damaged based on the gumming, translucent flesh, and scarring between the irrigated and non-irrigated mangosteen productions. All tests employed two-tailed hypothesis testing at a significance level of $p < 0.05$.

3. Results

3.1. Climatic and Soil Characteristics between Irrigated and Non-Irrigated Mangosteen Productions

Air temperature and soil temperature were significantly reduced in irrigated mangosteen production compared to non-irrigated, likely due to evaporative cooling from increased water availability. Conversely, relative humidity and soil moisture were significantly higher in irrigated systems (Table 1).

Table 1. Climatic and soil Characteristics in irrigated and non-irrigated mangosteen productions (P* < 0.001)**

Parameters	Mangosteen Production		*t*-test
	Irrigated	Non-Irrigated	
Climatic Parameter			
Air temperature (ºC)	28.26 ± 4.61	28.89 ± 5.74	$t_{47353.149} = -14.251^*$
Relative humidity (%)	93.78 ±13.14	91.29 ± 15.17	$t_{45853.869} = 20.101^*$
Soil Parameter			
Soil moisture (cb)	481.91 ± 188.23	843.11 ± 258.21	$t_{19466.081} = -78.977^*$
Soil temperature (ºC)	27.99 ± 1.88	29.11 ± 0.76	$t_{21538.875} = -180.176^*$

3.2. Mangosteen Fruit Damage between Irrigated and Non-Irrigated Mangosteen Productions

Diameter at breast height (DBH), crown width (CW), and fruit circumference (FC) did not differ between the irrigated and non-irrigated mangosteen productions (DBH_i: 59.80±8.84, DBH_n (59.60±8.21), t_{38} = 1.106, *ns*; CW_i: 3.18±0.27, CW_n: 3.09±0.26, t_{38} = 0.074, *ns*; FC_i: 17.55±1.15, FC_n: 17.54±1.09, t_{398} = 0.04, *ns*). Irrigated cultivation displayed a demonstrably enhanced reproductive capacity compared to non-irrigated mangosteen trees. Results showed a significantly increased floral and fruit set. Irrigation in mangosteen production exhibited significantly higher weight, overall yield, and decreased pulp segments than non-irrigated ones. Irrigation significantly influenced peel characteristics and internal fruit quality. Irrigated fruits showed thinner skins, decreased gummosis (gummy exudate formation), less translucent pulp, and scarring compared to non-irrigated fruits. These findings indicate that irrigation likely influences fruit development patterns and modifies specific quality attributes beyond size and yield (Figure 3a-h). The study categorized fruit damage, including translucent flesh, gumming, and scarring, into three levels of severity for each type: 0%, 1-25%, and 26-50%. Among mangosteen fruits, the percentages of translucent flesh, fruit gumming, and fruit scars were considerably lower in irrigated production, suggesting a potential positive impact of irrigation on fruit quality (Table 2).

Table 2. Mangosteen fruit damage between irrigated and non-irrigated mangosteen productions (P* < 0.05, ***P* < 0.001)**

Mangosteen	Irrigated (n = 200)		Non-Irrigated (n = 200)		Chi-Squared Test
	Fruits	(%)	Fruits	(%)	
Translucent flesh (%)					X_2^2= 48.191**
0%	177	88.50	116	58.00	
1-25%	18	9.00	73	36.50	
26-50%	5	2.50	11	5.50	
Fruit gumming (%)					X_2^2=6.409*
0%	188	94.00	173	86.50	
1-25%	10	5.00	22	11.00	
26-50%	2	1.00	5	2.50	
Fruit scars (%)					X_2^2=67.403**
0%	61	30.50	12	6.00	
1-25%	113	56.50	100	50.00	
26-50%	26	13.00	88	44.00	

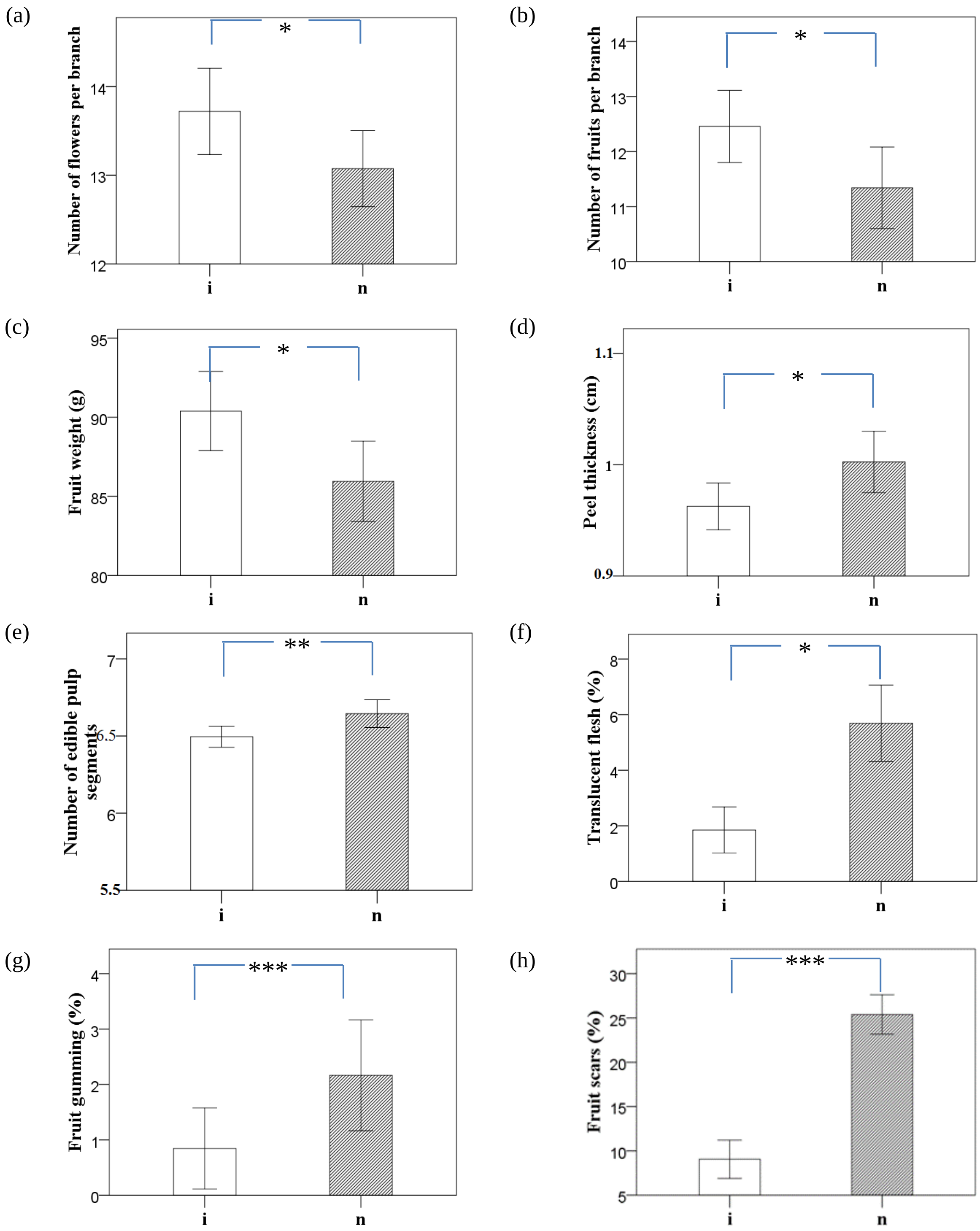


Figure 3. Mangosteen characteristics in the irrigated (i) and non-irrigated (n) mangosteen productions: (a) Number of flowers/branch, (b) Number of fruits/branch, (c) Fruit weight (g), (d) Peel thickness (cm), (e) Number of pulp segments, (f) Translucent flesh (%), (g) Fruit gumming (%), and (h) Fruit scars (%). (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$).

4. Discussion

4.1. Climatic and Soil Parameters

Our results demonstrate that irrigation significantly reduced air temperature, soil moisture, and soil temperature in mangosteen production. Irrigation in mangosteen production demonstrably changed the microclimate surrounding the trees. Compared to non-irrigated conditions, increased evapotranspiration under irrigation (right image) likely contributed to significantly lower air and soil temperatures. This cooling effect can be attributed to the latent heat absorbed during water evaporation from leaves and soil surfaces. Unveiling the complex interplay between water management, stress physiology, and blooming patterns in mangosteen holds paramount importance for optimizing irrigation practices and boosting fruit production in tropical settings. Understanding how specific water stress levels influence floral development empowers farmers to tailor irrigation regimes for enhanced mangosteen yield and economic return. Mangosteen growers can create the ideal conditions for mangosteen trees to thrive and produce bountiful harvests by carefully managing irrigation. Certain fruit trees, like mangoes and durians, require a dry period to induce flowering and fruit set [25–26]. Our results showed that irrigation significantly enhanced floral initiation, as evidenced by the increased number of flowers per branch in mangosteen trees. For fruits to reach their full potential in size, sweetness, and overall appeal, a steady moisture supply is essential during critical phenological stages, such as cell division and sugar accumulation [27]. A plant water deficit arises when transpiration exceeds water uptake due to insufficient soil moisture, disrupting cell enlargement and turgor pressure, hindering fruit expansion [28]. Fruit water content comes from both xylem (roots) and phloem (sugars). The xylem is the main player in water delivery to mangosteen trees. At the same time, the phloem plays an essential role in fruit expansion, carrying dissolved sugars, acting as an osmotic attractant, drawing water into the developing fruit cells, and contributing to their juiciness [29]. Like other tropical fruits, low soil moisture in a root area induces mangosteen flowering [22]. Soil temperature is important for mangosteen nutrient transformation and uptake by roots, vegetative growth, and reproduction regulated by various factors such as soil color, moisture, compaction, amount of vegetation cover, ambient temperature, and amount of sunlight available [30].

The timing of mangosteen flowering exhibits sensitivity to environmental cues, including regional climatic conditions, geographic location (e.g., latitude and altitude), and variations in light availability due to shade [22, 24, 31]. Our findings suggest that transient water stress induced by 14 days of reduced soil water potential acts as a signal for mangosteen trees, initiating physiological processes associated with floral development, including likely hormonal signaling and resource allocation. However, maintaining consistently low moisture levels is essential for successful floral maturation [22, 32–36]. In a surprising adaptation, previous studies have revealed that drought stress can act as a trigger for flowering in various plant species, likely through mechanisms involving stress-related hormones and the reallocation of resources towards reproductive development, such as durian [25], mango [32], citrus [33], longan [34], lime [35], loquat [36], mangosteen [22, 37], and star fruit [38]. Mangosteen trees, adapted to monsoonal environments, exhibit a unique dependence on a dry period of a minimum of 15 days for optimal flower bud initiation. This physiological adaptation likely evolved to synchronize flowering with the onset of the rainy season, ensuring adequate water availability for fruit development and maximizing reproductive success. This mechanism ensures synchronized flowering coincides with reliable rainfall patterns for successful fruit development and seed dispersal [22, 37]. Stress from drought induces flowering, which is positively correlated with carbohydrates accumulated in leaves, xylem, and phloem in apples [39, 40], litchis [41], and star fruits [38]. Drought-induced mangosteen flowering knowledge could be the key to developing drought-resistant varieties, optimizing irrigation practices, and safeguarding this delicious fruit's future.

4.2. Mangosteen Fruit Quality

Our study revealed that irrigated trees produced fruits weighing 3 g higher, had less edible pulp segment, and had a peel thickness than their non-irrigated counterparts. Thinner skin from irrigated mangosteens might offer less protection during storage and transport. A previous study reported that drought severely hinders custard apple growth 4-6 weeks after fruit set, causing an 11% reduction in size due to disrupted cell division and compromised carbon assimilation [42]. A plant water deficit, triggered by insufficient soil moisture, can significantly hinder fruit expansion. This stress disrupts water uptake and transport within the plant, reducing turgor pressure in fruit cells and ultimately halting or slowing down their growth [28]. In addition, fruit weight also depends on the age and geographical location of mangosteen trees. Reduced resource availability and limited canopy development in younger mangosteen trees likely constrain fruit size compared to mature trees, which possess established root systems and greater photosynthetic capacity [24]. Mangosteen fruit size exhibits geographical variation, with fruits from the southern Philippines typically exceeding the average size observed in the Malay Peninsula [24]. Several studies reported that smart irrigation deficit techniques could dramatically reduce water usage while simultaneously amplifying crop productivity such as maize [43], potato [44], and tomato [45] and in plant species such as apple [46, 47], almond [44], peach [48], and pear [49]. By mitigating water stress and preventing associated foliar injuries, irrigation promotes the optimal functioning of the photosynthetic apparatus in trees, maximizing light capture and CO_2 fixation, ultimately translating to increased biomass production and yield [50].

4.3. Fruit Damage

Our study revealed that irrigated mangosteens exhibit significantly lower rates of gumming, translucence, and scarring, resulting in superior fruit quality. Reduced stress and physiological disorders associated with improved water balance under irrigation might contribute to fewer mangosteen fruit damages (i.e., translucent flesh, fruit gumming, and fruit scars) observed compared to non-irrigated conditions. Translucent flesh disorders in fruits are associated with various factors, including mechanical injury during harvesting [51], imbalances in nutrient uptake [51], pathogenic infections [52], and excessive water uptake by the fruit [53]. Our study showed that the number of translucent-fleshed fruits increased after the mangosteens received disproportionate water uptake into the flesh during development and growth, such as after heavy rainfalls for more than five days. The translucent-fleshed disorder in mangosteen fruits is similar to the water core in apples (*Malus domestica* Borkh.) [54], and durians (*Durio zibethinus* Murr.) [55]. Fresh mangosteen arils transform, ripening, and transitioning from an opaque white color to a translucent appearance.

Simultaneously, the texture shifts from soft and succulent to crisp and firm. These changes likely reflect cell wall polysaccharides' degradation and pectin composition alterations, leading to increased light transmission and altered tissue rigidity [53, 56]. Pre-harvest exposure to excessive water intake can trigger translucent flesh disease in fruits, driven by a gradient in osmotic potential between rainwater and the fruit cells. This excessive water leads to passive water influx and potentially compromised cell wall integrity [39]. Mangosteen fruits with high water content lead to apoplast or symplasm splitting, causing a translucent texture [39]. Developing the aqueous core is a maturation phenomenon associated with leaky cell membranes or altered transport in susceptible cultivars [54]. The core of the durian (*Durio zibethinus* Murr.) was wet due to excessive moisture caused by heavy rain, resulting in the softening of the durian core and pulp due to excess moisture [55].

Mangosteen gumming occurs when the rind or flesh becomes yellow [53, 56]. This dramatic shift in water pressure creates a mighty rush, pulling water and solutes into the fruit, ultimately causing the gumming [18]. Fruit gumming in the mangosteen trees occurred when soil moisture was at the critical value of -100 kPa soil moisture, and then the mangosteen trees were rewatered suddenly [18]. A previous study demonstrated how overwatering disrupted physiological processes and led to cracked shells. Studies report that elevated water uptake during specific developmental stages can induce fruit cracking in pecans [57], sweet cherries [58], and tomatoes [59], potentially due to rapid cell expansion exceeding the elastic limits of the fruit's outer tissues, leading to ruptures. Rapid fluctuations in water levels can induce water stress in plants, leading to imbalances in turgor pressure and potentially causing cell wall expansion and rupture. This cell wall expansion can occur due to the inability of plant cells to adjust their water content quickly enough to maintain their structural integrity [20, 60]. Our research suggests that regulating water flux between soil and fruit can mitigate physiological imbalances leading to translucent flesh and gumming disorders, potentially through optimized cell wall integrity and metabolic processes. The threshold of mangosteen gumming is nine weeks of excess water after flowering [39]. Mangosteen growers could reduce the chance of mangosteen gumming by regulating irrigation to keep the soil moisture constant after mangosteen flowering.

Exceeding 70 g per fruit with no fruit defect is a baseline for export-quality mangosteens [61]. Thrip and mite infestations represent significant economic threats to mangosteen production, as their feeding damage translates into reduced fruit quality and marketability due to the prevalence of unsightly scars and blemishes. Fruit scarring in mangosteen is attributed to infestations by specific thrips species, including *Scirtothrips dorsalis* Hood, *Scirtothrips oligocheatus* Karny, and *Selenothrips rubrocinctus* (Giard), as well as *Tetranychus* spp. mites [61]. Increased air temperature and decreased relative humidity positively correlate with thrip abundance, suggesting enhanced survival and reproductive success under warmer and drier conditions [62]. Understanding the complex interplay between individual climatic factors and thrip population dynamics can inform the development of predictive models and targeted pest management strategies in agriculturally relevant contexts. Implementing a multipronged approach that combines reducing air temperature, increasing relative humidity), and blocking wind flow can effectively suppress thrip populations in orchards. This strategy leverages the combined effects of these environmental factors to create an unfavorable habitat for thrips and hinder their reproduction and survival. Wind flow can play a vital role in thrip abundance by dispersing thrips [63]. Irrigation management can keep air temperature low and provide high relative humidity, preventing thrips outbreaks. In addition, a mangosteen mixed cropping system can reduce a thrip movement. Non-host plants alter the landscape, disrupting thrip movement, making it difficult for thrips to reach the fruits and repelling the pest with their hairy leaves and thorns.

5. Conclusion

Precise soil moisture monitoring eliminates the risk of overwatering or underwatering, ensuring optimal water utilization for efficient mangosteen growth and fruit production. This study emphasizes the extensive perspective of soil moisture sensors and IoT in revolutionizing irrigation practices for mangosteen production. By employing a network of strategically placed sensors that continuously monitor soil moisture levels in real time, farmers can transition from traditional, schedule-based irrigation to a data-driven approach. The observed decrease in gumming, translucence, and scarring underlines the critical role of regulated water supply in minimizing fruit imperfections and maximizing marketable yield. By maintaining optimal soil moisture conditions, this technology boosts fruit quantity and quality and fosters resource-efficient water management, enabling the transition to a more sustainable and profitable mangosteen farming system.

6. Declarations

6.1. Author Contributions

Conceptualization, M.J. and K.J.; methodology, M.J. and K.J.; formal analysis, K.J., M.J., and P.B.; investigation, K.J., M.J., and P.B.; data curation, K.J. and P.B.; writing—original draft preparation, K.J., P.B., M.J., and E.B.S.; writing—review and editing, K.J., P.B., M.J., and E.B.S. 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.

6.3. Funding

We sincerely thank the Center of Excellence for Ecoinformatics, Walailak University, for its invaluable support and resources, and OHEC for providing funding through the Talent Mobility Project (Grant Number SCH021).

6.4. Acknowledgements

This work owes a deep debt of gratitude to the thoughtful and insightful reviewers for their valuable contributions in the form of insightful comments and suggestions. Their feedback significantly improved the quality and clarity of our work. The language and editing Expertise of Carol S. John, David C. Chang and Dr. Curt Barnes significantly enhanced the presentation of our research. We are immensely thankful for their thoughtful suggestions and revisions of previous drafts.

6.5. Institutional Review Board Statement

Not applicable.

6.6. Informed Consent Statement

Not applicable.

6.7. Declaration of Competing Interest

The authors declare that there is no conflict of interests 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] Jain, R. K. (2023). Experimental performance of smart IoT-enabled drip irrigation system using and controlled through web-based applications. Smart Agricultural Technology, 4, 100215. doi:10.1016/j.atech.2023.100215.

[2] Kumar S, V., Singh, C. D., Rao, K. V. R., Kumar, M., Rajwade, Y. A., Babu, B., & Singh, K. (2023). Evaluation of IoT based smart drip irrigation and ETC based system for sweet corn. Smart Agricultural Technology, 5, 100248. doi:10.1016/j.atech.2023.100248.

[3] Delgoda, D., Malano, H., Saleem, S. K., & Halgamuge, M. N. (2016). Irrigation control based on model predictive control (MPC): Formulation of theory and validation using weather forecast data and AQUACROP model. Environmental Modelling and Software, 78, 40–53. doi:10.1016/j.envsoft.2015.12.012.

[4] Soulis, K. X., & Elmaloglou, S. (2018). Optimum soil water content sensors placement for surface drip irrigation scheduling in layered soils. Computers and Electronics in Agriculture, 152, 1–8. doi:10.1016/j.compag.2018.06.052.

[5] Gadissa, T., & Chemeda, D. (2009). Effects of drip irrigation levels and planting methods on yield and yield components of green pepper (*Capsicum annuum*, L.) in Bako, Ethiopia. Agricultural Water Management, 96(11), 1673–1678. doi:10.1016/j.agwat.2009.07.004.

[6] Hassan, I. F., Gaballah, M. S., El-Hoseiny, H. M., El-Sharnouby, M. E., & Alam-Eldein, S. M. (2021). Deficit irrigation to enhance fruit quality of the 'African Rose' plum under the Egyptian semi-arid conditions. Agronomy, 11(7), 1405. doi:10.3390/agronomy11071405.

[7] Chen, F., Cui, N., Jiang, S., Li, H., Wang, Y., Gong, D., Hu, X., Zhao, L., Liu, C., & Qiu, R. (2022). Effects of water deficit at different growth stages under drip irrigation on fruit quality of citrus in the humid areas of South China. Agricultural Water Management, 262, 107407. doi:10.1016/j.agwat.2021.107407.

[8] Hajian, G., Ghasemnezhad, M., Fotouhi Ghazvini, R., & Khaledian, M. R. (2020). Effects of regulated deficit irrigation on vegetative growth, fruit yield and quality of Japanese plum (*Prunus salicina* Lindell 'Methly'). Agriculture Conspectus Scientificus, 85(1), 61–70.

[9] Sun, G., Hu, T., Liu, X., Peng, Y., Leng, X., Li, Y., & Yang, Q. (2022). Optimizing irrigation and fertilization at various growth stages to improve mango yield, fruit quality and water-fertilizer use efficiency in xerothermic regions. Agricultural Water Management, 260, 107296. doi:10.1016/j.agwat.2021.107296.

[10] Gucci, R., Caruso, G., Gennai, C., Esposto, S., Urbani, S., & Servili, M. (2019). Fruit growth, yield and oil quality changes induced by deficit irrigation at different stages of olive fruit development. Agricultural Water Management, 212, 88–98. doi:10.1016/j.agwat.2018.08.022.

[11] Canatário Duarte, A., Veloso, A., Ramos, A., Ferreira, D., & Simões, M. P. (2020). Deficit Irrigation in Peach Orchards under Water Scarcity Conditions. KnE Engineering, 7, 716–727. doi:10.18502/keg.v5i6.7092.

[12] Kabir, M. Y., Nambeesan, S. U., Bautista, J., & Díaz-Pérez, J. C. (2021). Effect of irrigation level on plant growth, physiology and fruit yield and quality in bell pepper (*Capsicum annuum* L.). Scientia Horticulture, 281, 109902. doi:10.1016/j.scienta.2021.109902.

[13] Yao, Z., Hou, X., Wang, Y., & Du, T. (2023). Regulation of tomato yield and fruit quality by alternate partial root-zone irrigation strongly depends on truss positions. Agricultural Water Management, 282, 108288. doi:10.1016/j.agwat.2023.108288.

[14] Kasikorn Research (2021). Thai mangosteen exports to grow 14.6-18.8 percent in 2021...despite short-term supply disruption. Agriculture, 3259. Available online: https://www.kasikornresearch.com/en/analysis/k-econ/business/Pages/mangosteen-z3259.aspx (accessed on March 2024).

[15] Jarimopas, B., Pushpariksha, P., & Singh, S. P. (2009). Postharvest damage of mangosteen and quality grading using mechanical and optical properties as indicators. International Journal of Food Properties, 12(2), 414–426. doi:10.1080/10942910701837262.

[16] Sayekti, A. L., Hayati, N. Q., Sulistyaningrum, A., Sjafrina, N., Mulyono, D., Anwarudinsyah, M. J., Hafizah, D., & Prabawati, S. (2023). The policy impacts and implications from the insights of mangosteen export chains. IOP Conference Series: Earth and Environmental Science, 1153(1), 12014. doi:10.1088/1755-1315/1153/1/012014.

[17] Pechkeo, S., Nilnond, C., & Sdoodee, S. (2013). Feasibility study to alleviate the translucent flesh and gamboge disorders of mangosteen (*Garcinia mangostana* L.) by spraying with calcium chloride. Acta Horticulture, 975, 441–448. doi:10.17660/actahortic.2013.975.57.

[18] Sdoodee, S., & Limpun-Udom, S. (2002). Effect of excess water on the incidence of translucent flesh disorder in mangosteen (*Garcinia mangostana* L.). Acta Horticulturae, 575, 813–820. doi:10.17660/ActaHortic.2002.575.96.

[19] Lobet, G., Couvreur, V., Meunier, F., Javaux, M., & Draye, X. (2014). Plant water uptake in drying soils. Plant Physiology, 164(4), 1619–1627. doi:10.1104/pp.113.233486.

[20] Poerwanto, R., Efendi, D., Sobir, & Suhartanto, R. (2008). Improving productivity and quality of Indonesian mangosteen. Acta Horticulturae, 769, 285–288. doi:10.17660/ActaHortic.2008.769.41.

[21] Bin Osman, M., & Milan, A. R. (2006). Mangosteen-Garcinia mangostana L. Southampton Centre for Underutilized Crops, University of Southampton, Southampton, England.

[22] Jaroensutasinee, K., Jaroensutasinee, M., & Boonsanong, P. (2023). Climatic Factor Differences and Mangosteen Fruit Quality between On-and Off-Season Productions. Emerging Science Journal, 7(2), 578–588. doi:10.28991/ESJ-2023-07-02-020.

[23] Setiawan, E., Poerwanto, R., Fukuda, F., & Kubota, N. (2012). Meteorological Conditions of Mangosteen Orchard in West Java, Indonesia and Seasonal Changes in C-N Ratio of Their Leaves as Affected by Sector (Position in Canopy) and Tree Age. Science Report of the Faculty of Agriculture, Okayama University, 101, 39–47.

[24] Yaacob, O., & Tindall, H. D. (1995). Mangosteen Cultivation. FAO Plant Protection Paper 129. Food and Agriculture Organization of the United Nations, Rome, Italy. doi:10.5962/bhl.title.121365.

[25] Nakasone, H. Y., & Paull, R. E. (1998). Durian. In Tropical Fruit, H. Y. Nakasone, and R. E. Paull, eds. Wallingford, UK: CAB International, 341–351.

[26] 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.

[27] Ganeshamurthy, A. N., & Reddy, Y. T. N. (2015). Fitness of Mango for Colonization in Low Fertility Soils and Dry Lands: Examination of Leaf Life-Span, Leaf Nutrient Resorption, and Nutrient Use Efficiency in Elite Mango Varieties. Agricultural Research, 4(3), 254–260. doi:10.1007/s40003-015-0164-8.

[28] Naor, A. (2001). Irrigation and crop load influence fruit size and water relations in field-grown "Spadona" pear. Journal of the American Society for Horticultural Science, 126(2), 252–255. doi:10.21273/jashs.126.2.252.

[29] Nerd, A., & Nobel, P. S. (2000). Water relations during ripening for fruit of well-watered versus water-stressed *Opuntia ficus-indica*. Journal of the American Society for Horticultural Science, 125(5), 653–657. doi:10.21273/jashs.125.5.653.

[30] Chowdhury, S., Bolan, N., Farrell, M., Sarkar, B., Sarker, J. R., Kirkham, M. B., Hossain, M. Z., & Kim, G. H. (2021). Role of cultural and nutrient management practices in carbon sequestration in agricultural soil. Advances in Agronomy, 166, 131–196. doi:10.1016/bs.agron.2020.10.001.

[31] 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.

[32] Núñez-Elisea, R., & Davenport, T. L. (1994). Flowering of mango trees in containers as influenced by seasonal temperature and water stress. Scientia Horticulturae, 58(1–2), 57–66. doi:10.1016/0304-4238(94)90127-9.

[33] Koshita, Y., & Takahara, T. (2004). Effect of water stress on flower-bud formation and plant hormone content of satsuma mandarin (*Citrus unshiu* Marc.). Scientia Horticulturae, 99(3–4), 301–307. doi:10.1016/S0304-4238(03)00113-4.

[34] Sritontip, C., Jaroenkit, T., Manochai, P., & Sangchyoswat, C. (2014). The impact of climate changes on yield of longan production in Northern Thailand. Acta Horticulturae, 1029, 155–162. doi:10.17660/ActaHortic.2014.1029.17.

[35] Southwick, S. M., & Davenport, T. L. (1986). Characterization of Water Stress and Low Temperature Effects on Flower Induction in Citrus. Plant Physiology, 81(1), 26–29. doi:10.1104/pp.81.1.26.

[36] Fernández, M. D., Hueso, J. J., & Cuevas, J. (2010). Water stress integral for successful modification of flowering dates in "Algerie" loquat. Irrigation Science, 28(2), 127–134. doi:10.1007/s00271-009-0165-0.

[37] Boonklong, O., Jaroensutasinee, M., & Jaroensutasinee, K. (2006). Climate Change Affecting Mangosteen Production in Thailand. Proceedings of the 5th WSEAS International Conference on Environment, Ecosystems and Development, 1, 325–332.

[38] WU, P., WU, C., & ZHOU, B. (2017). Drought Stress Induces Flowering and Enhances Carbohydrate Accumulation in *Averrhoa carambola*. Horticultural Plant Journal, 3(2), 60–66. doi:10.1016/j.hpj.2017.07.008.

[39] 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 and Technology, 27(5), 957-965.

[40] 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.

[41] Yang, H. F., Kim, H. J., Chen, H. Bin, Rahman, J., Lu, X. Y., & Zhou, B. Y. (2014). Carbohydrate accumulation and flowering-related gene expression levels at different developmental stages of terminal shoots in *Litchi chinensis*. HortScience, 49(11), 1381–1391. doi:10.21273/hortsci.49.11.1381.

[42] George, A. P., & Nissen, R. J. (2002). Effects of drought on fruit set, yield and quality of custard apple (*Annona* spp. hybrid) "African Pride" plants. Journal of Horticultural Science & Biotechnology, 77(4), 418–427. doi:10.1080/14620316.2002.11511515.

[43] Li, C. X., Zhou, X. G., Sun, J. S., Wang, H. Z., & Gao, Y. (2014). Dynamics of root water uptake and water use efficiency under alternate partial root-zone irrigation. Desalination and Water Treatment, 52(13–15), 2805–2810. doi:10.1080/19443994.2013.822647.

[44] Xie, K., Wang, X. X., Zhang, R., Gong, X., Zhang, S., Mares, V., Gavilán, C., Posadas, A., & Quiroz, R. (2012). Partial root-zone drying irrigation and water utilization efficiency by the potato crop in semi-arid regions in China. Scientia Horticulturae, 134, 20–25. doi:10.1016/j.scienta.2011.11.034.

[45] Wang, Y., Liu, F., Andersen, M. N., & Jensen, C. R. (2010). Improved plant nitrogen nutrition contributes to higher water use efficiency in tomatoes under alternate partial root-zone irrigation. Functional Plant Biology, 37(2), 175–182. doi:10.1071/FP09181.

[46] Van Hooijdonk, B. M., Dorji, K., & Behboudian, M. H. (2004). Responses of 'Pacific Rose' TM apple to partial root zone drying and to deficit irrigation. European Journal of Horticultural Science, 69(3), 104–110.

[47] Egea, G., Dodd, I. C., González-Real, M. M., Domingo, R., & Baille, A. (2011). Partial rootzone drying improves almond tree leaf-level water use efficiency and afternoon water status compared with regulated deficit irrigation. Functional Plant Biology, 38(5), 372–385. doi:10.1071/FP10247.

[48] Geiiy, M., Recasens, I., Girona, J., Mata, M., Arbones, A., Rufat, J., & Marsal, J. (2004). Effects of stage II and postharvest deficit irrigation on peach quality during maturation and after cold storage. Journal of the Science of Food and Agriculture, 84(6), 561–568. doi:10.1002/jsfa.1686.

[49] Cui, N., Du, T., Kang, S., Li, F., Hu, X., Wang, M., & Li, Z. (2009). Relationship between stable carbon isotope discrimination and water use efficiency under regulated deficit irrigation of pear-jujube tree. Agricultural Water Management, 96(11), 1615–1622. doi:10.1016/j.agwat.2009.06.009.

[50] Vijayakumar, K. R., Dey, S. K., Chandrasekhar, T. R., Devakumar, A. S., Mohankrishna, T., Sanjeeva Rao, P., & Sethuraj, M. R. (1998). Irrigation requirement of rubber trees (*Hevea brasiliensis*) in the subhumid tropics. Agricultural Water Management, 35(3), 245–259. doi:10.1016/S0378-3774(97)00019-X.

[51] Phlompaat, N. (1989). Mangosteen for exporting. Thai Fruit Tree Assn., Bangkok, Thailand.

[52] Wannasiri, S. (1990). Mangosteen. Rural Agricultural Center of Thailand, Bangkok, Thailand.

[53] Pankasemsuk, T., Garner, J. O., Matta, F. B., & Silva, J. L. (1996). Translucent flesh disorder of mangosteen fruit (*Garcinia mangostana* L.). HortScience, 31(1), 112–113. doi:10.21273/hortsci.31.1.112.

[54] Marlow, G., & W. Loescher. (1984). Watercore. Horticultural Reviews, 6, 189-251.

[55] Sapii, A. T., & Nanthachai, S. (1994). Physiological disorders, Durian, fruit development, postharvest physiology, handling and marketing in ASEAN (5th ed). ASEAN Food Handling Bureau, Kuala Lumpur, Malaysia.

[56] Teerachaichayut, S., Terdwongworakul, A., & Pathaveerat, S. (2008). Multiple parameters for prediction of translucent flesh in mangosteens. Agricultural Engineering International, CIGR Ejournal. Manuscript FP 08 007. Vol. X. December, 2008.

[57] Wood, B. W., & Reilly, C. C. (1999). Factors influencing water split of pecan fruit. HortScience, 34(2), 215–217. doi:10.21273/hortsci.34.2.215.

[58] Lane, W. D., Meheriuk, M., & McKenzie, D. L. (2000). Fruit cracking of a susceptible, an intermediate, and a resistant sweet cherry cultivar. HortScience, 35(2), 239–242. doi:10.21273/hortsci.35.2.239.

[59] Peet, M. M., & Willits, D. H. (1995). Role of excess water in tomato fruit cracking. HortScience, 30(1), 65–68. doi:10.21273/hortsci.30.1.65.

[60] Fauziana, D. R., Suwarsinah, H. K., & Prasetio, E. A. (2023). What factors impact the adoption of postharvest loss-reduction technologies in mangosteen supply chain? Journal of Open Innovation: Technology, Market, and Complexity, 9(3), 100102. doi:10.1016/j.joitmc.2023.100102.

[61] Pankeaw, K., Ngampongsai, A., Permkam, S., & Rukadee, O. (2011). Abundance and distribution of thrips (Thysanoptera: Thripidae) in mangosteen (*Garcinia mangostana* L.) grown in single- and mixed-cropping systems. Songklanakarin Journal of Science and Technology, 33(3), 263–269.

[62] Emilda, D. (2010). Effect of mulching, sanitation and yellow fluorescent sticky trap application on population fluctuation and critical attack period of thrip on mangosteen. AGRIVITA Journal of Agricultural Science, 32(3), 277-284.

[63] Pearsall, I. A., & Myers, J. H. (2000). Population dynamics of western flower thrips (Thysanoptera: Thripidae) in nectarine orchards in British Columbia. Journal of Economic Entomology, 93(2), 264-275. doi:10.1603/0022-0493-93.2.264.