

# Using microdendrometers and microtensiometers for mango irrigation scheduling: a review

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## Abstract

**In the past two decades, there have been significant advancements in plant-based technologies for orchard irrigation scheduling. One method that has shown rapid progress in recent years involves precise measurements of micro-variations in stem or twig diameter. Micro-dendrometers have emerged as a promising tool for creating fully automated irrigation scheduling systems, thanks to their exceptional robustness, reliability, and accuracy in real-world conditions. A recent breakthrough in micro-tensiometer technology has enabled direct and accurate measurement of stem water potential over the long-term. The significant improvement in sensor technology, mobile communication, and machine learning has further driven the development of plant-based irrigation scheduling technology and its automation. Commercial irrigation scheduling systems based on microdendrometer and microtensiometer have emerged and gained rapid adoption by tree crop farmers. This paper reviewed studies spanning the 1990s to the 2020s on microdendrometer and microtensiometer measurements of mango trees. The research highlights the potential of these sensors to inform irrigation scheduling on mango farms. We further explored the latest commercially available irrigation scheduling systems utilizing microdendrometers and microtensiometers. By examining the underlying technology and business models, we assessed their accessibility for mango growers. Finally, we provide insights and suggestions for those considering adopting these technologies.**

**Keywords:** plant-based indicator, automated irrigation system, daily growth, daily maximum shrinkage, plant water status

## INTRODUCTION

In the past two decades, numerous plant-based methods have been developed for informing irrigation scheduling of tree crops (Jones, 2004; Lu, 2006; Fernández and Cuevas, 2010; Lakso and Intrigliolo, 2022). One method that has shown significant progress involves precise measurements of micro-variations in stem or twig diameter (shrinkage and expansion) using micro-dendrometers. These devices are known for their robustness and reliability, making them ideal to be used for the automation of irrigation scheduling (Jones, 2004; Fernández and Cuevas, 2010; Lu, 2013; Fernández, 2017; Noun et al., 2022). A recent breakthrough in microtensiometer development has made long-term direct and accurate measurement of stem water potential a reality (Lakso et al., 2022). Advances in sensor technology, mobile communication, and machine learning have further accelerated the development of automated irrigation systems, with many tree crop farmers, including mango farmers already utilizing commercial systems based on microdendrometers or microtensiometers.

Fernández and Cuevas (2010) and Lakso et al. (2022) provided comprehensive reviews on using dendrometers and microtensiometers for irrigation scheduling, respectively. We avoid reiterating their work; interested readers can refer to their reviews for details.

Importantly, from a plant physiology and irrigation agronomy perspective, stem water potential and stem diameter variations exhibit remarkable similarities, with some sensor-

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specific distinctions. Consequently, insights gained from one method are largely transferable to the other.

This paper reviews existing published and unpublished studies on using microdendrometers (Lu, 2006, 2013; Hahn and Garcia, 2022a,b) and microtensiometers (FlorPulse, unpublished) for mango irrigation. We explore their potential to inform and potentially even automate irrigation scheduling on mango farms.

We will then delve into the latest commercially available irrigation scheduling systems that utilize microdendrometers and microtensiometers. Here, we will explore the underlying technology and the business models to assess their accessibility for mango growers. Finally, we will provide insights and suggestions for those considering adopting this technology.

## STUDIES ON MANGO TREES USING MICRODENDROMETERS AND MICROTENSIOMETERS

A pressure chamber is a conventional method to measure leaf or twig water potential, thus the tree water status (Shackel et al., 2021). However, due to abundant latex in the mango xylem, data from pressure chamber measurements are not reliable for many mango cultivars, especially for Australia's dominant mango cultivar 'Kensington Pride' (Lu, 2002).

In the 1990s in search for a reliable indicator of whole tree water status in mango, the author (Lu, 2002, 2006, 2013) extensively examined the suitability of sap flow (Granier's TDP method; Granier, 1985; Lu et al., 2004), diameter variation (LVDT type microdendrometer, Li et al., 1989; Figure 1), leaf water potential (pressure chamber), stem water potential (stem psychrometer; Dixon and Tyree, 1984), canopy temperature (InfraRed camera; Jones, 2004), and leaf gas exchange (Li-Cor 6400), with concurrent measurements of weather and soil moisture (CS616 FDR, and EnviroScan).

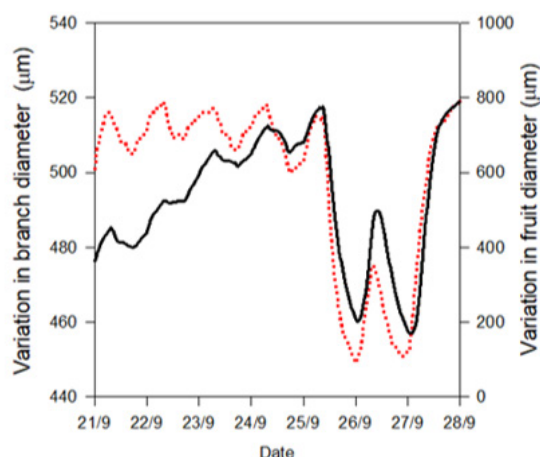


Figure 1. (Left) A microdendrometer using LVDT sensor (Linear variable displacement transducers, PEPISTA, France) installed on a twig of a mango tree; (Right) Diurnal changes in the diameter of a branch (red, pointed line) and fruit (black, unbroken line) on a 3-year-old mango ('Kensington Pride') tree grown in a 200L plastic drum. Irrigation was turned off from September 23, 1996 onwards, in Darwin, Australia (Lu, 2006).

They found that in mango trees, as in other tree crops studied by Li et al. (1989), the time course of several days of diurnal variation of diameter is informative (Figure 2). The two most useful indices derived from stem, branch, or fruit diameter variation, the daily growth (DG, net increase in maximum diameters over two consecutive nights) and the daily maximum shrinkage<sup>b</sup> (DMS, the difference between maximum and minimum diameters recorded during

<sup>b</sup>The term daily maximum shrinkage is preferred over maximum daily shrinkage.

a calendar day), as well as their trending, are the most important and often the only information necessary to schedule irrigation in mango.

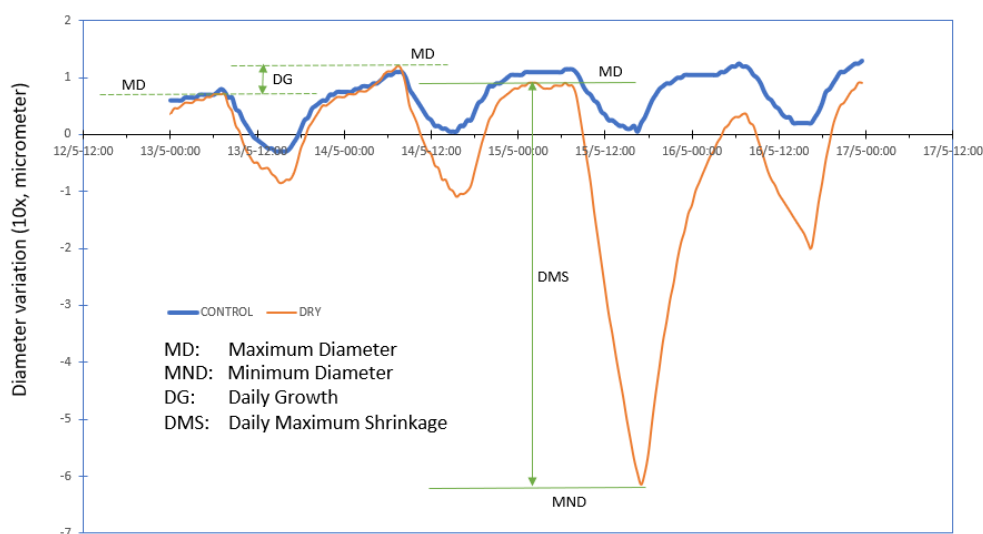


Figure 2. Diurnal changes in branch diameter variation of 3-year-old ‘Irwin’ mango trees under dry condition vs. control condition, grown in 200-L plastic drums, Darwin, Australia. Control tree was irrigated every night, dry tree received a similar amount of water as the control on the night of May 13, 1996, then only received 10% of the normal irrigation amount on the night of May 15 and 16, 1996 (Ping Lu, unpublished).

Under normal mango growing conditions in an irrigation season, in sunny or cloudy conditions, during vegetative or reproductive stages, if the following scenarios occur on consecutive days, it indicates the plant is in a corresponding water status as shown in Table 1.

Table 1. Scenarios of the diameter variation as shown by indices daily growth (DG) and daily maximum shrinkage (DMS) and interpretation of the water status and recommended actions.

Scenarios	Water status, and actions
DG >0, DMS no significant increase	Good growth, no water stress, maintain the same irrigation routine, or no irrigation needed
DG=0 or ≈0, and DMS no significant ↑ over 2-4 consecutive days	No growth, watching and warning
DG=0 or slightly > 0, and DMS ↑ significant on a day	No growth, tree is starting to struggle with meeting water requirements, irrigate now
DG <0, DMS ↑ increasing over 2-4 consecutive days	No growth, the tree is increasingly struggling with meeting water requirements, irrigate immediately
If at the above stage, if no extra water, and DG <0 for more days, and DMS ↓	Severe water stress, irrigate immediately, and even use canopy pruning to recover the tree

These interpretations and recommended actions hold true for low-frequency irrigation such as daily, every two days, or at longer intervals, in Darwin, Australia. It might also be true for twice daily irrigation system. It was found also true for mango trees of ‘Kensington Pride’, ‘Irwin’ and ‘Nam Doc Mai’, of trees of 3-15 years old, and measured on either branch, stem, or fruits (Lu, unpublished). These observations and interpretations are consistent with those

reported in the above-mentioned reviews.

In the above studies as shown in Figure 1 (right panel), they also observed that during 7 days, the fruit size fluctuated by more than 600  $\mu\text{m}$ , while the twig, as depicted in the left panel, only varied by less than 70  $\mu\text{m}$ . The small branch is more sensitive to water stress compared to the fruit. This observation holds for mango trees during the rapid fruit expansion phase, which is crucial for fruit size development. While nearly all of the studies in the literature used the stem dendrometer, we found that the small branches are the best part of the tree to obtain a long-term reliable data set (further discussion under Discussion and Conclusion).

From these initial studies, it was concluded that considering the level of the sensor technology at the time both Granier sap flow and LVDT microdendrometer were the two most promising methods for automated continuous monitoring of whole tree water status in mango (Lu, 2002, 2006, 2013).

After further studies using both sap flow and microdendrometer methods to schedule irrigation in a commercial mango orchard and monitor mango physiology under different horticultural practices (Lu et al., 2017), the microdendrometer was found to be a more robust and reliable method under field conditions than the sap flow method. Sap flow sensors have more delicate electronic elements and signals are more sensitive to ambient thermal interference (Lu, 2013).

In the field experiment where mango productivity and quality, as well as irrigation water efficiency, were compared among three treatments (dendrometer controlled, soil moisture sensors controlled, and 80% evaporation replacement) (Lu, 2006, 2013). Irrigation controlled by dendrometers using the shrinkage index as an indicator had better irrigation efficiency than the other two treatments, amounting to 77% of irrigation water used by mango trees (Lu, 2006, 2013). The fruit quality (Brix and panel tastings) was also higher than the other two treatments (Lu, unpublished).

In another study where dendrometers were used to assess the water status of trunk strangulated mango trees (Lu et al., 2017), a surrogate of the whole-tree hydraulic conductance (Lu et al., 1996) that is normally derived from the correlation between diurnal variations of sap flux density and xylem potential was satisfactorily generated by using concurrently measured sap flux density and branch diameter variation data. This demonstrated that the diurnal diameter microvariation is linearly correlated with the xylem water potential like that has been directly demonstrated in other tree crops (Cochard et al., 2001).

They also found that the dendrometer has a long maintenance-free period (up to 3-4 months that covers the entire mango flowering and fruiting period if measured on a twig of 5-10 mm diameter) and the indices derived from their measurements are more sensitive to plant water stress than the sap flow method in mango.

Recently in a 2019-2020 study, mango stem variation was examined under different irrigation regimes in Mexico (Hahn and Garcia, 2022a). They used a homemade dendrometer based on a linear resistor to provide a voltage output according to the trunk diameter. This new type of dendrometer is not as accurate and reliable as the LVDT sensors in the field conditions. Although their sensors captured some diurnal variations in stem diameter and the authors were able to observe some patterns corresponding to phenological stages, it seems that the dendrometers used still need further improvement. One evident issue might be related to the saturated signals during the night time as shown in their figures. However, in a later study (Hahn and Garcia, 2022b) daily growth was evident and they concluded that "(their) dendrometers are able to monitor quick changes in mango trees" which suggests that their dendrometer has been improved.

Despite the limited published results of micro-dendrometer studies on mango trees, it is evident that diameter variation measured using microdendrometers is a good plant water status indicator and it could be utilized for guiding mango irrigation scheduling. Further research by physiologists and agronomists is needed to establish the threshold points of those indices for controlling irrigation at different phenological stages, enabling growers to effectively utilize dendrometers for irrigation scheduling.

## COMMERCIALIZED PLANT-BASED IRRIGATION SCHEDULING SYSTEMS

### System based on microdendrometer

The very first commercial irrigation scheduling system based on microdendrometers was the PEPISTA developed in France in the 1980s-1990s. Unfortunately, it seems that the company Agro-Technologie ([www.agro-technologies.com](http://www.agro-technologies.com)) no longer markets this product. Several companies are currently commercializing such irrigation scheduling systems: Verdtech ([verdtech.es](http://verdtech.es)), Semios ([semios.com](http://semios.com)), and Phytech ([www.phytech.com](http://www.phytech.com)), with Phytech likely having the widest reach in the tree crops industry.

Phytech, an Israeli company, was founded in 2011 and it sells an IoT (Internet of Things<sup>4</sup>) platform to farmers that consists of proprietary dendrometer sensors and algorithms for crops. The system optimizes irrigation based on accurate real-time data from the plant (using a microdendrometer). It provides the users with an app that displays what the farm needs, from stressed plots, irrigation performance, weather forecasts, and Phytech's irrigation recommendations (Figure 3).



Figure 3. Left) Phytech website page showing the dendrometer attached to the stem and the app provided to the users (Phytech.com); Right) A FloraPulse sensor is installed in a tree stem and information is presented in an app (FloraPulse.com). Note that for both companies, the water status is colour-coded based on an understanding of the impact of the water status on tree physiology and performance.

The Phytech system seems to be commercialized as a subscription package to the customers and it seems that the business operates on the hardware-as-a-service, i.e., rather than paying outright to own a piece of hardware, the customer pays a subscription for access to the value, utility, or function associated with that hardware. The systems have now been used on a variety of crops, including almonds, apples, cherries, avocado, kiwi, soybeans, and corn. It is claimed that they also offer a fully automated solution as they are using machine learning in optimizing irrigation management (Phytech.com). So far, no use on mango farms has been reported.

### System based on microtensiometer

Tree crop scientists have long dreamed of a sensor that can offer accurate and continuous real-time stem water potential data to monitor plant water status and optimize irrigation management. This dream is now a reality with the development of the FloraPulse microtensiometer by Alan Lakso, Professor of Plant Science, and Abraham Stroock, Professor of Chemical and Biomolecular Engineering at Cornell University. This innovative sensor marks a breakthrough in stem water potential sensor technology (Lakso et al., 2022). The FloraPulse system features a microchip tensiometer embedded within the tree woody tissue, providing continuous and accurate measurement of water status, known as water potential. This

<sup>4</sup>Internet of Things, also called IOT, is a network of physical devices. These devices can transfer data to one another without human intervention.

innovative instrument offers the accuracy of a pressure chamber without the limitations of manual measurement.

Since its commercial launch in 2018, FloraPulse has been enhancing its product robustness and reliability to support woody crop growers. Currently, they offer an all-inclusive subscription including all things necessary for a user to start improving irrigation management, such as sensors, cellular-powered dataloggers, data connectivity, visualization tools, warranty, and probe replacements (Figure 3, right panel). The subscribers have access to real-time data on stem water potential and receive weekly science-based reports. The data comes in the form of an app that plots daily stem water potential against thresholds based either on recommendations from University California Davis for almonds or prunes or by working with wine grape growers to set their own (FloraPulse.com, 2024). Currently, the subscription is available only in limited regions, and its geographic reach seems not as extensive as the Phyttech.

The FloraPulse shared with us a data set from their preliminary microtensiometer tests on a mango tree over 5 months (Figure 4). Without weather and soil moisture information, it is difficult to interpret the result more than the sensor signal values and the pattern. The raw data are plausible and show satisfactory long-term performance of the sensor. According to a video testimony (FloraPulse.com), one mango grower in California, USA grows a rare mango crop, in a desert environment with extremely high summer temperatures, in alluvium soil that has very limited water holding capacity. They had been using soil moisture measurement units but was always nervous that the soil moisture information is not completely indicative of the requirements of the mango trees, particularly when they get in the 115 to 120°F temperature range. They had four separate high temperature incidences in a recent summer that lasted 3 to 5 days each and using the FloraPulse information he modified the irrigation frequency, run time, or added an extra irrigation cycle to meet the needs of the trees. They have achieved an additional 10% annual reduction in water usage by utilizing this innovative technology.

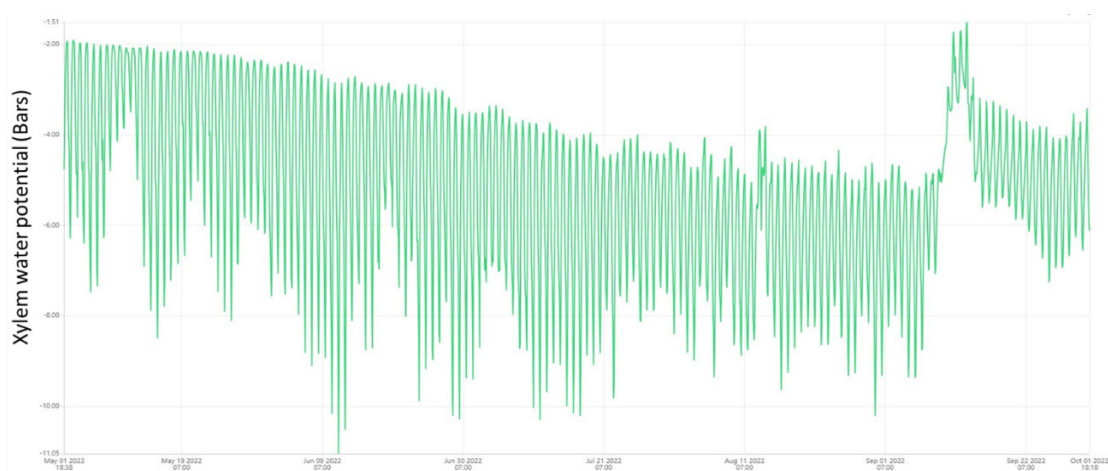


Figure 4. A preliminary result from a test of microtensiometer on a mango tree over 5 months. Courtesy from Maryrose Lund, FloraPulse, unpublished data.

While the system is not fully automated yet, FloraPulse aims to assist growers in optimizing their irrigation practices. With an increasing understanding of crop water dynamics and their impact on fruit growth and quality, a fully automated option may become feasible, especially given the advancements in artificial intelligence (AI) decision-making technology.

## DISCUSSION AND CONCLUSIONS

### Challenges and considerations for microdendrometer use in mango

Mango trees, being fast-growing tropical species, pose unique challenges for microdendrometer use. Microdendrometers (based on LVDT sensors) have a defined measurement range (stroke) that varies by sensor model/type. This means mango trees, with their rapid growth, may require more frequent adjustments (resetting) compared to slower-growing temperate tree crops. Sensors with a smaller stroke will necessitate more frequent readjustments/resetting in the field, leading to a shorter maintenance-free period.

Our extensive testing on mango trees revealed that measurements on various tree parts, including the main trunk, main branches, small brown-barked branches, green 5-10 mm branches/twigs, and even fruits, can readily reveal plant water status. Interestingly, small branches (5-10 mm diameter) displayed the greatest sensitivity, likely due to a combination of factors:

- Sufficient maturity and structural strength for sensor mounting (balance of rigidity and elasticity);
- Thinner bark and relatively elastic wood enable the microdendrometer to capture subtler changes in water potential.

Fruits exhibited lower sensitivity compared to small branches, this difference can be attributed to two main factors:

- A fruit's higher thermal expansion coefficient due to its higher starch content could partially offset shrinkage caused by water deficit;
- A developing fruit is the strongest sink which draws in water and carbohydrates due to its high osmotic potential, further mitigating shrinkage.

Thick-barked parts, like the main stem, likely have the lowest sensitivity due to the thicker bark and more rigid tissues hindering the detection of subtle changes in water potential.

### Small branches: ideal for long-term mango monitoring

Tropical mango orchards, with their high winds during fruiting season, present a unique challenge for long-term sensor-based monitoring. While attaching sensors to the main stem offers stability, it requires larger and costlier equipment. Conversely, sensors on fruits are highly susceptible to wind damage.

The ideal location lies within the inner canopy, on small branches. These branches can sway with the wind without compromising data collection. Additionally, their smaller size allows for less expensive, lightweight sensors, minimizing breakage risks. Furthermore, due to their smaller girth, these branches require less frequent readjustment compared to larger ones, extending the maintenance-free period. Finally, our unpublished data suggests that shrinkage patterns within and between trees are more consistent when using branches of similar size and orientation. This offers a valuable, yet currently under-reported, approach in the scientific literature.

### Evaluating the FloraPulse system for mango irrigation

The commercially available FloraPulse system holds promise as an automated irrigation tool. However, intrusive sensors like microtensiometers might face long-term reliability issues due to various factors impacting their performance in mango trees, specifically the presence of latex. Further field trials are necessary, integrating concurrent weather data, soil moisture sensors, and probably also microdendrometers. These trials will rigorously assess FloraPulse's effectiveness for mango irrigation and potentially refine sensor design for latex-rich species.

### Microdendrometers: a promising solution

Based on current knowledge, microdendrometers measuring diameter changes on small branches (0.5-1 cm) appear to be the most promising approach. These sensors are less intrusive, potentially requiring minimal to no maintenance or adjustments throughout the

growing or irrigation season.

### **Potential and challenges for automated mango irrigation**

A high correlation between stem diameter variation and stem water potential, suggests potential for interchangeable use in irrigation control algorithms. However, successful interpretation and decision-making based on stem diameter variation time series requires not just indices like daily growth (DG) and daily maximum shrinkage (DMS) but also trend analysis of the signal. While human assessment of trends is relatively straightforward, automated analysis through traditional computing methods can be challenging.

Machine learning offers promising solutions for trend analysis, interpretation, and stress detection in diameter variation data. This development, coupled with advancements in sensor technology and control systems, paves the way for commercially available automated irrigation systems for some crops within the next few years.

### **Adoption in mango production**

While automated irrigation systems for key tree crops like apple, pear, and pecan might be readily available in the coming decade, the picture for mango is less clear. This delay is primarily due to the fragmented nature of the mango industry, its current level of technological adoption, and resource limitations. Individual operation sizes, limited industry cooperation, and financial constraints likely hinder widespread automation implementation in mango production at this stage.

### **Focus on crop-specific knowledge**

Despite the rapid development in sensor and control technology, the critical challenge lies in algorithm development for robust decision-making. Effective crop irrigation automation necessitates a deep understanding of how plant water status, as measured by diameter variation or stem water potential, influences fruit growth and quality across different phenological stages.

Herein lies the crucial role of mango agronomists. Building a comprehensive knowledge base on mango water needs, establishing irrigation thresholds for each phenological stage, and ensuring this technology translates into a valuable tool for farmers are paramount. This knowledge base should consider cultivar variations and regional differences.

### **Concluding: research before adoption**

While commercially available plant-based automated irrigation systems hold promise, their current application in mango production may be limited by our understanding of mango physiology and irrigation needs. These systems might generate non-specific recommendations, leading to more frustration than benefit for growers.

Therefore, in the next 3-5 years, we strongly encourage mango researchers to leverage these systems for in-depth research. Building a robust knowledge base for diverse mango cultivars and regions will pave the way for the successful adoption of mature, crop-specific automation technology by mango growers.

### **ACKNOWLEDGEMENTS**

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