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Assessment of Continuous Apple Growth Under Dynamic Agrivoltaic Systems Using Fruit Dendrometry

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Abstract. Heat stress could negatively impact apple fruit growth. In this study shading with a dynamic agrivoltaic system (DAV) during summer was tested to evaluate if a less stressful environment can maintain fruit growth by improving water flows to the fruit. The study was conducted in an experimental 'Golden' apple orchard in France in 2023 with a control zone and a zone protected with DAV. Air temperature and incident radiation at the tree level was continuously measured for each zone. Fruit growth and vascular fluxes were continuously measured by using fruit dendrometers during summer (between May and September). Twelve fruits per zone were monitored according to three different conditions: 'intact' fruits (i.e. normal vascular connections), 'girdled' fruit (i.e. disconnected from the phloem, and 'detached' fruit (i.e. disconnected from both phloem and xylem). Daily courses of leaf, stem and fruit water potential were measured one day during summer. A reduction of 50% of incident daily radiation and air temperature was observed in the DAV zone. Absolute growth rate in DAV fruits was higher than the control when temperatures were higher than 30°C. The less stressful environment improved tree organ water status, supporting a better fruit hydration despite a potential reduction of xylem intake. This mechanism seems enough to maintain fruit size in trees shaded with DAV.

Keywords: Climate Change, Fruit Growth, Malus Domestica, Shading Crops, Vascular Flows

1. Introduction

Climate change increases the intensity and frequency of extreme weather events that could negatively affect apple growth and yield [1], [2], [3]. High temperature reduces fruit growth due to attenuated photosynthetic activity and water stress among other factors [4], [5]. Fruit growth is a complex mechanism which involves several biochemical and biophysical processes that contribute to the accumulation of fresh and dry mass [6]. The primary factors driving fruit growth include water, carbohydrates, and minerals, which are transported through the xylem and phloem. The xylem flow to the fruit follows the potential gradient and the hydraulic conductance of xylem vessels. Dynamic agrivoltaics (DAV) has been proposed to generate a less stressful environment by shading trees during heatwaves and maintain fruit growth [7]. Apple fresh weight was maintained when maximal shading with solar panels was applied [4]. It was hypothesized that by improving tree water status under shade, these conditions may have increased the water potential gradient between the stems and the fruits, increasing the water import to the fruit and compensating a potential reduction of carbohydrates due to the shading conditions [4]. It is important to mention that shading may have also altered actual fruit growth due to modifications in the loss of water and transpiration through xylem backflow. No study has evaluated if a less stressful environment in DAV conditions alters fruit transpiration and water losses [7]. The objectives of this study were: 1) to evaluate the impact of shading with a DAV system on apple fruit growth measured continuously with fruit dendrometers, and 2) to evaluate the relative contribution of organ water potential and xylem, phloem, transpiration fluxes under shaded condition during periods with contrasting air temperatures.

2. Material and methods

2.1 Experimental orchard

The study was performed in a ‘Golden Delicious’ apple (*Malus x domestica* Borkh.) orchard located in the experimental station of La Pugère (Mallemort, France: 43.74 N; 5.125 E). The trees were planted in 2010 in a north-south orientation (16° east). The orchard had nine rows, two of which were considered border trees. Each row had a total of 60 trees. The distance between trees was 1.25 m within rows and the inter-row distance was 4 m. A DAV system was installed in February 2019 above the trees. The structure was positioned 5 m above the ground and the photovoltaic axis height was 5.4 m. The DAV zone covered 735 m^2. 1482 m^2 were not covered with solar panels and was considered the control (CTRL) (Figure 1). The solar modules (PW2450F, Photowatt, France) are mounted on pivot tables around a single-axis solar tracker. The system allows the movement of the solar modules +/- 90° from east to west, allowing the maximal shading of trees or the total exposure to sunlight. The ratio of area of photovoltaic panels to area of land is 0.42. An anti-hail net was installed during the fruit growing season on both control and DAV zones, reducing the light by 10%. The irrigation system consisted of a micro-sprinkler system with one emitter per two trees and a flow rate of 35 l/h. Irrigation was managed to avoid water deficit. CTRL trees require more irrigation than DAV trees to have a similar soil moisture [4].

Between 2019 and 2022, the panels were always in tracking position as reported in [4]. In summer 2023, the position of the panels included a period with similar conditions of light between the CTRL and the DAV zones (antitracking) and a period with maximal shading in the DAV zone (full-tracking). The 28th of June represents the transition between anti-tracking and full tracking. In 2023, solar panels were always placed in tracking position (maximal shading for the trees) when air temperature was above a given threshold. Calendar dates are also expressed as days after bloom (DAFB) to compare with other studies in the literature. In 2023, the trees reached full bloom on the 13th of April.

Figure 1. *General view of the apple dynamic agrivoltaic system (left) and detail of a fruit gauge and a node to collect fruit diameter variation continuously in the orchard (right).*

2.2 Measurements

To monitor the microclimate at the tree level, two Davis weather stations (Vantage Pro 2, Davis, France) were installed for each zone, containing a thermo-hygrometer, a pluviometer, a pyranometer, and an anemometer. These stations were installed in the central part of each zone (below the nets for the control trees and below the nets and solar panels for the agrivoltaic zone).

Fruit diameter variation was assessed continuously with dendrometers. Fruit gauges (Megatron Elektronik MM10, 50 KΩ; Megatron Elektronik AG & Co., Munich, Germany) were installed on three trees with a similar commercial crop load in the central row of the orchard for the CRTL and DAV zone. These sensors were installed on the 30th of May (47 DAFB) on 24 fruits (12 per treatment). These fruit gauges were adjusted two times per week regulating the piston stroke to capture the variation of fruit growth changing the population of fruit when necessary. Fruit diameter variation was followed for three categories of fruit: ‘intact’ fruits (i.e. normal vascular connections), ‘girdled’ fruit (i.e. disconnected from the phloem, and ‘detached’ fruit (i.e. disconnected from both phloem and xylem) [8]. Fruit gauges were connected to three different nodes, solar and battery powered, and the diameter variation were recorded every 15 minutes (Figure 1). Continuous growth and the three different categories of fruits allowed the calculation of absolute growth rate (AGR) and vascular flows as reported in [8]. This method also required to calculate a diameter-weight conversion equation during the study, to determine the absolute growth rate (AGR), expressed as the mean hourly change in fruit weight [8]. To do that, ten fruits were randomly collected for each treatment 54, 63, 69, 76, 88, 97,106 and 110 DAFB. Vascular flows and absolute growth rate (AGR) were analysed over four different periods, considering the first two analysed periods when DAV was in anti-tracking and the last two were always in full-tracking (shading the trees during the whole day). For each period, to estimate phloem contribution for a given interval of time (two days), the mean AGR of ‘intact’ fruits was subtracted from the mean AGR of ‘girdled’ fruits [8]. To estimate the xylem contribution, the mean AGR of ‘girdled’ fruit was subtracted from the mean AGR of ‘detached’ fruits [8]. The transpiration contribution corresponds to changes in ‘detached’ fruit [8]. We restricted the analysis to interval times of two days to avoid excessive dehydration of the tissue of detached fruit, which could lead to an underestimated fruit transpiration.

Additionally, individual fruit dry matter concentration was determined for the eight samples of fruits mentioned above because shading can alter dry matter due to a modification of the water status of the tree [4]. Individual fruit fresh weight was measured first. Then, all fruits were dried in an oven at 69°C, until they reached a constant weight. Fruit dry matter concentration was calculated dividing the dry weight by the fresh weight and multiply by 100.

Midday stem water potential was measured for nine trees in the CRTL and DAV trees on the 19th of July (97 DAFB) and the first of August (110 DAFB). For each tree, a fully developed mature leaf located near the base of the trunk was selected. The selected leaves were covered with aluminium bags one hour before measurements. The measurements were conducted using a pressure chamber (PMS600, PMS Instrument Company, USA). At 110 DAFB, water potential of four leaves, stems and fruits per treatment were collected doing three measurements per day (morning, midday, and afternoon). For each vascular flow trait, midday water potential, and fruit dry matter concentration a t-test was used to compare the mean values of the CTRL and DAV.

3. Results and discussion

This study has been done when the orchard was covered with an anti-hail net likely allowing greater diffuse light penetration into the canopy for both the CTRL and DAV zones than other apple studies done without anti-hail nets. Under these experimental conditions, as reported in

[9], there was a slight reduction of about 10% in the daily light integral (DLI) due to the agrivoltaic structure during the anti-tracking period in 2023. The reduction in DLI reached almost 50% after shading the trees with the full-tracking policy [9]. Air temperature for DAV trees was lower than for the CTRL trees during the tracking-periods due to the light reduction while it remained similar during the anti-tracking period [9].

When DAV was in anti-tracking and temperatures were lower than 30°C (Figure 2a, 64-66 DAFB period), higher transpiration was observed for DAV fruit, however, in terms of vascular flows, no differences were reported with the CTRL. Gained growth peaked at 1.6 g, with no significant difference between CTRL and DAV. Xylem contribution reached almost 1.7 g and transpiration losses reached a maximum value of -1.7 g. During the 71-72 DAFB period (Figure 2b), temperatures were higher at 72 DAFB, and panels were in tracking mode for heat protection for several hours. DAV exhibited a marginally higher phloem intake, xylem intake and transpiration losses, that finally resulted in a significant higher growth under DAV.

Figure 3 presents results obtained when the steering policy switched to full-tracking during the whole day. For the period 108-109 DAFB (Figure 3a), recorded temperatures were always higher than 30°C. In the DAV, shading significantly reduced transpiration losses connected to a lower xylem inflow, while maintaining a general accumulation of gained growth and phloem intake. For the last period (112-113 DAFB) (Figure 3b), when temperatures were lower than 30°C again, xylem contribution was significantly higher in the DAV, despite no significant differences in transpiration losses, phloem intake, and gained growth.

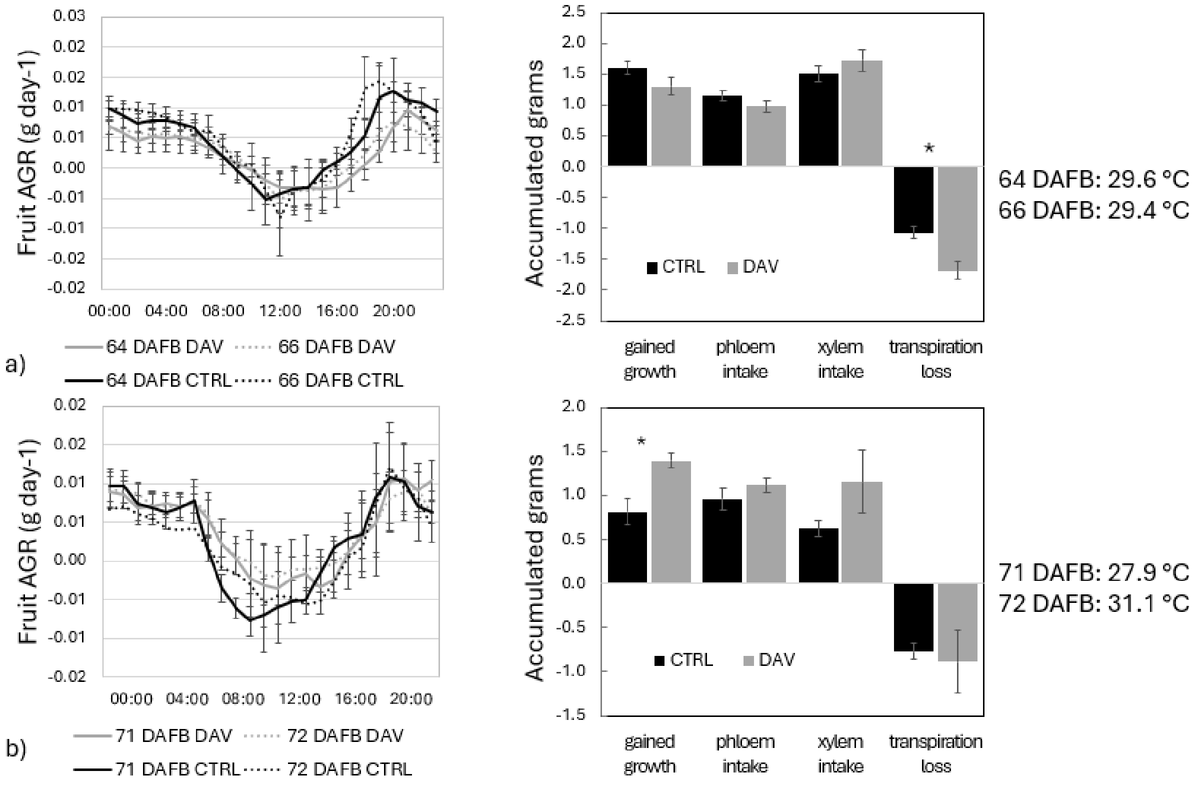

Figure 2. *Average accumulations of gained growth, phloem intake, xylem intake and transpiration loss during anti tracking for two different periods: a) 16-18 June (64-66 DAFB), b) 23-24 June (71-72 DAFB). Abbreviations: * = significant differences at p ≤ 0.05 according to student’s t test.*

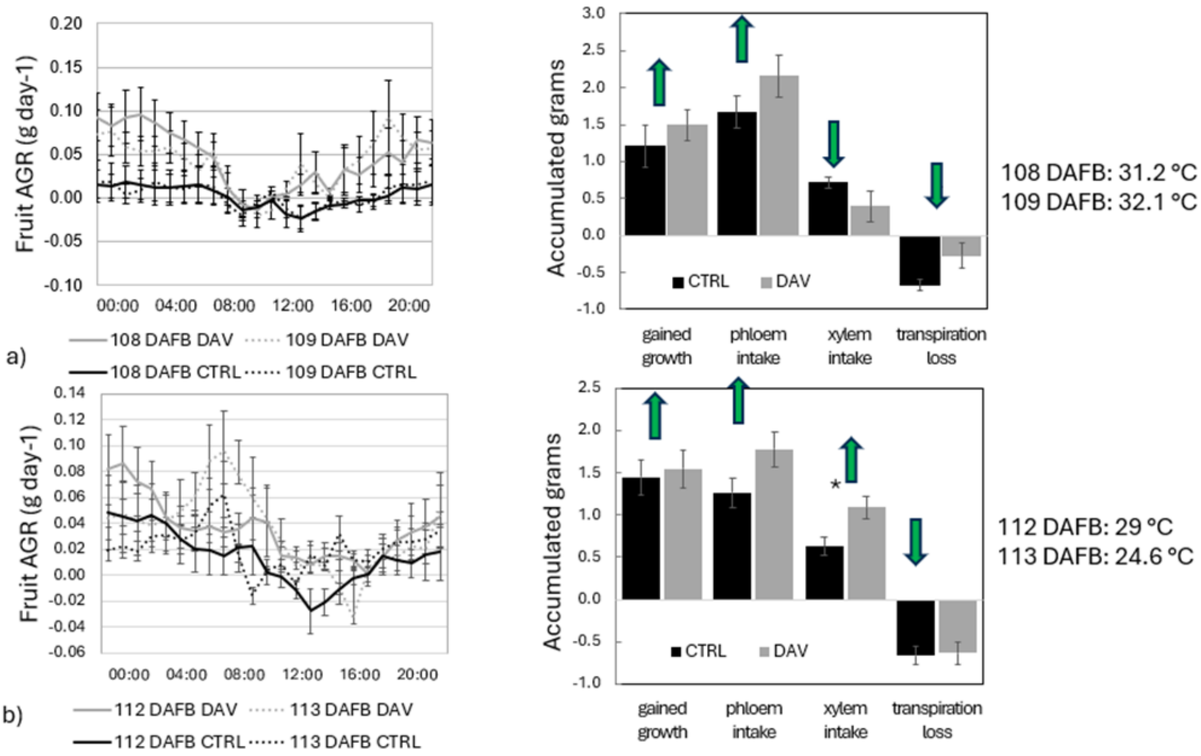

Figure 3. *Average accumulations of gained growth, phloem intake, xylem intake and transpiration loss during full tracking for two different periods for control (CTRL) and agrivoltaic trees (DAV): a) 30-31 July (108-109 DAFB), b) 3-4 August (112-113 DAFB). Green arrows have been added to help interpreting the graphs. Abbreviations: * = significant differences at p ≤ 0.05 according to student’s t test.*

Under DAV, midday stem water potential was always less negative, indicating a better tree water status (Figure 4). Since apple growth is very sensitive to water stress, this better water status under the DAV could be a benefit for the apple growth. This better water status was also observed in the stems, leaves, and fruits (Figure 5).

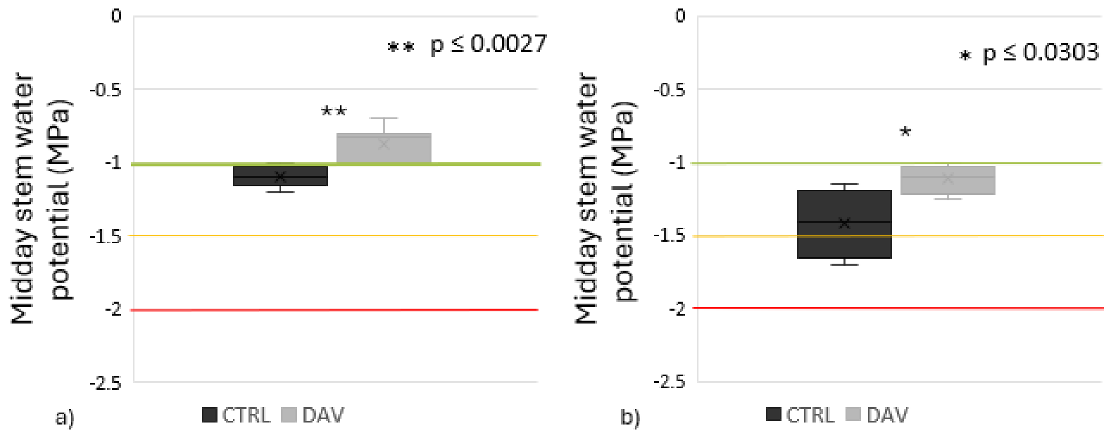

Figure 4. *Boxplots of midday stem water potential for control (CTRL) and agrivoltaic trees (DAV) on nine selected leaves on nine different trees per treatment on the 19th of July (97 DAFB) (a) and on the 1st of August (110 DAFB) (b) Abbreviations: * = significant differences at p ≤ 0.05, ** = significant differences at p ≤ 0.01 according to student’s t test.*

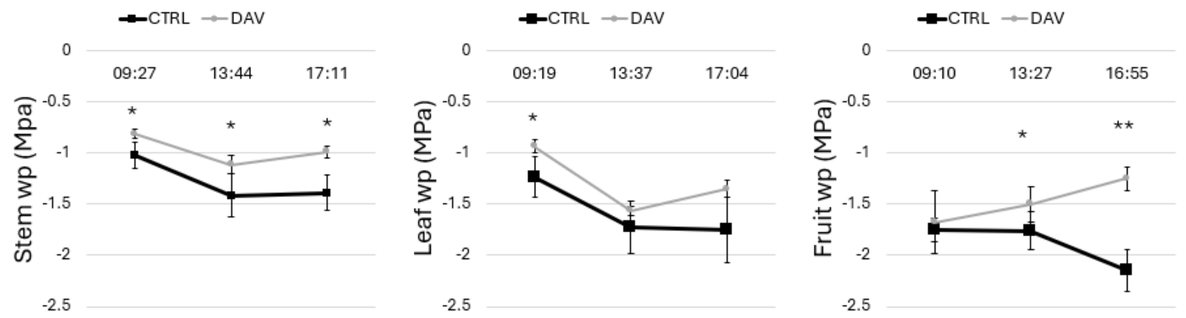

Figure 5. *Daily patterns of stem, leaf and fruit water potential (wp) for control (CTRL) and agrivoltaic system (DAV) on four selected leaves on four different trees per treatment on the 1st of August (110 DAFB). Abbreviations: * = significant differences at p ≤ 0.05, ** = significant differences at p ≤ 0.01 according to student's t test.*

During the day, except for the first measurement for the fruits, water potential of different organs was always less negative in the DAV treatment with the highest differences for the fruits late in the afternoon (Figure 5). Figure 6 shows the last three measurements of dry matter concentration in the fruits throughout the experiment. With time, CTRL fruits accumulate significantly more dry matter than their DAV counterpart potentially linked to a lower photosynthesis in the shade of panels. This leads to a higher osmotic pressure in CTRL fruits.

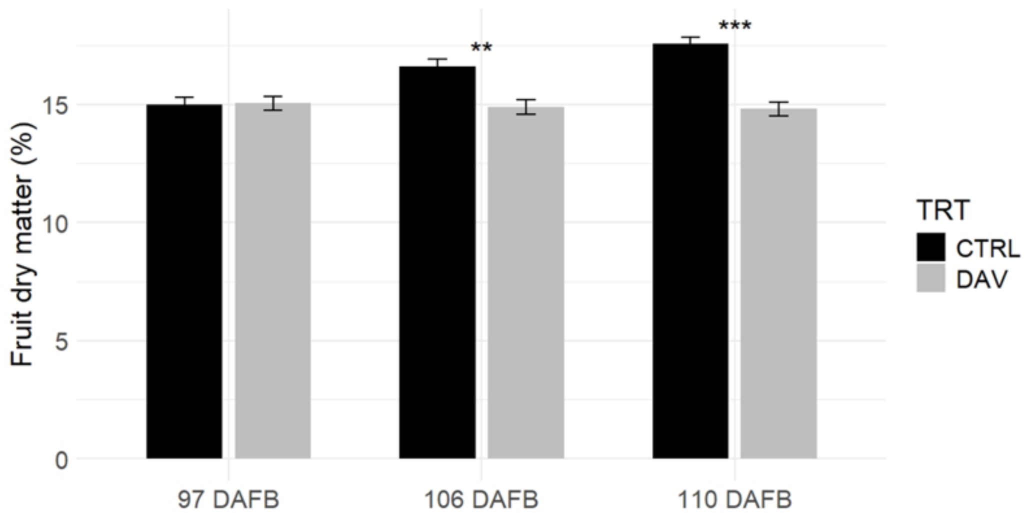

Figure 6. *Fruit dry matter concentration for the last three sampling dates of the study (a) 19 July (97 DAFB), b) 28 July (106 DAFB), c) 01 August (110 DAFB) for control (CTRL) and agrivoltaic system (DAV). Abbreviations: ** = significant differences at p ≤ 0.01, *** = significant differences at p ≤ 0.001 according to student's t test.*

In 2023, there was no significant difference in final fruit size between CTRL and DAV despite the trajectory of DAV fruits growth being above CTRL throughout the season [9]. Fruit growth is determined by water inflow [10]. This inflow is driven by the difference between fruit water potential (mostly osmotic potential) and stem water potential minus the loss by transpiration. Similar measurements in other apple studies indicated that the xylem contribution to fruit growth decreases with the development of the apple fruit [11], [12]. We observed that there was no significant difference between fruit transpiration in both treatments except when fruits were shaded during days with air temperature above 30°C. Inflow of water from the xylem was always higher in DAV fruits, linked to better tree water status. There was a notable exception in DAFB 109 which could be explained by the strong reduction in transpiration. However, shading the trees also induces less carbon assimilation by leaves [4] and therefore a lower sugar content in the phloem which may limit the flux towards the fruits. We observed that the higher water influx in the fruit potentially led to a dilution effect and an even lower osmotic potential in the fruit maintaining higher influx from the phloem compared to CTRL fruits. All these components concur to explain the trend observed on fruit growth.

4. Conclusion

Previous studies indicated a better tree water status [4] and a trend to increase fruit size [9] when apple trees receive full-tracking during the whole day. This study adds complementary measurements of organ water potential and vascular flows, using fruit dendrometers to explain in which conditions apple fruit growth can be improved under the shade of a DAV system. DAV trees grown under a less stressful environment improved the stem, leaf and fruit water potential in comparison to the CTRL trees with measured benefits in terms of water fluxes to the fruit especially when temperatures were higher than 30°C. Daily fruit growth patterns varied in response to environmental conditions between the control and the DAV zone, particularly in days with high temperatures when trees were always shaded. Apple fruit performs better under shading conditions, reflecting different translocations of vascular fluxes; reducing fruit water losses, enhancing solute concentration via phloem, thus achieving optimal fruit weight gain during the most stressful periods of the year. In conclusion, apple can be shaded with DAV systems during the final period of growth, reducing irrigation needs without losing growth potential, mitigating the negative impacts of high temperatures due to climate change. This study only covers fruit growth in response to shading. Other important traits for apple production such as bloom return, fruit set, fruit coloration and composition need to be considered in further agrivoltaics studies.

Data availability statement

The data of this study are confidential.

Author contributions

AP, GL, and VH: Investigation. BM, AB, AP, GL and JC: Data curation, AP, AB, BM, GL: Writing – original draft. DF: Validation, Project administration.

Competing interests

The authors declare that they have no competing interests.

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