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Yield and fruit quality of the apple cultivars 'Freya®', 'Topaz', 'Natyra®', and 'Delcored®' after two years of agrivoltaics

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Abstract

This two-year study evaluated the effects of agrivoltaic (AV) systems on yield and fruit quality in organic apple production of the cultivars 'Freya®', 'Topaz', 'Natyra®', and 'Delcored®'. The experiment compared two AV configurations - single-axis tracking and fixed-tilt system both using semi-transparent solar panels (49% light transmission) - with a control covered with a standard grey hail net. Across cultivars, flowering intensity and yield in AV systems were slightly to moderately lower than in the control, especially in the second year. 'Topaz' and 'Delcored®' showed the best adaptation to AV conditions, maintaining 78-95% of control yields, whereas 'Freya®' and 'Natyra®' experienced stronger yield reductions. Fruit size was on average smaller and fruit red overcolour tended to be less pronounced in AV treatments for all cultivars. Harvest in AV conditions was delayed by one to two weeks compared to the control.

Keywords: agrivoltaics, AV systems, Agri-PV, agricultural photovoltaics, apple

Introduction

The basic idea behind agrivoltaics (AV) is the dual use of land for energy and crop production at the same time. The aim is to use land more efficiently while, in best case, also securing production conditions by adapting to climate change. The effects of changed growing conditions on crop production as well as the practicability and economic viability of agrivoltaics are being researched worldwide for a wide range of crops. At Kompetenzzentrum Obstbau Bodensee (KOB), a trial site for agrivoltaics production of organically managed dessert apples was established in 2022. The trial site is part of an initiative ("Modellregion Agri-Photovoltaik für Baden-Württemberg") launched and funded by the federal state of Baden-Württemberg. It comprises a growing number of agrivoltaics test sites covering pome and stone fruit experiments across the South of Germany. The sites are located both at practical farms and research institutes. Further information can be found at www.agripv-bw.de.

Material and Methods

Experimental Design. The trial site at KOB in Ravensburg (47.766788, 9.555617) covered 0.6 ha and comprised the experimental agrivoltaics (AV) treatments single-axis tracking and fixed-tilt system with a clear height of 3.5 m. These two AV treatments were compared with a control covered with grey hail net [Fig.1]. Both AV treatments used identical semi-transparent solar panels with a manufacturer-stated light transmission of 49%. The fixed-tilt treatment (fixed) was a static gable roof with a 10° east-west tilt, while the single-axis tiltable treatment (tracker) was also east-west oriented but consisted of tiltable panels that were set to optimize electricity production. During rainfall, the tracker was lying horizontal to maximize rain protection; in snow, it tilted steeply to reduce snow load and preserve stability. The panels (2.29 m × 1.13 m) were installed lengthwise on the fixed system and crosswise on the tracker. Despite construction differences, both treatments provided a nearly 2.3 m wide cover above the tree row. Both AV systems also had hail nets above the driving lanes to

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prevent side-impact hail damage. The control treatment was covered with grey hail net, which is considered a locally common protection system. The structure was completed prior to tree planting. Great care was taken to ensure that heavy construction machinery only passed through future driving lanes and not tree rows to prevent soil compaction in the root zone. Panel installation was completed in April 2022 in the fixed system but was delayed until June 2022 for the tracker, leaving trees there exposed to natural light for two months longer. Additional shading differences resulted from construction gaps, namely a 3 cm wide ridge gap in the fixed system and 32 cm structural gaps around the tracker posts.

Figure 1: Experimental treatments fixed-tilt system (fixed), single-axis tracking (tracker) and control.

In spring 2022, the apple cultivars ‘Freya®’, ‘Topaz’, ‘Natyra®’, and ‘Delcored®’, all on M9 rootstock, were planted at a spacing of ~1.0 × 3.5 m. Due to practical issues arising from large difference in harvest time, corresponding plant protection and constructional restrictions, plots were not completely randomized but cultivars were planted alternating per row. Thus, the four apple cultivars were planted in a total of 18 rows of 80 trees each, with cultivars alternating four times from row to row. To exclude possible fringe effects, only the middle 16 rows were evaluated. The three experimental treatments were installed transversely to the planting direction, leading to at least 20 test trees per row for each treatment. Accordingly, a sum of 80 trees (four rows x 20 trees) was the basis of the analyses in this study.

***Irrigation*.** Precipitation in the AV treatments was directed onto the driving lanes via the solar panels, while the control received natural precipitation directly. Additionally, all treatments had drip irrigation. The amounts of water given were controlled empirically rather than sensor-based with the goal to prevent drought stress. In the relatively dry growing season of 2023, trees in AV systems received 260 L/tree while trees in control only received 102 L/tree in addition to natural precipitation. In the wetter year of 2024, irrigation was reduced accordingly to 147 L/tree in AV treatments and 18 L/tree in control. No symptoms of drought stress were observed in any treatment and year.

***Data collection methods*.** Flowering intensity was visually assessed at 80 trees per treatment and cultivar on a scale of 1 (no flowers) to 9 (heavy blooming), with the optimal target range being 6–7. Thinning in both years was carried out exclusively by hand as required. The harvest date was determined visually based on red overcolour development and thus based on marketability. To calculate the average yield per tree, the fruit load of at least 80 trees per treatment and cultivar was weighed in the field during harvest at each picking and summed up over all pickings. Blemished fruits were at first included in the yield data and later separated manually during the mechanical sorting process. A sorting machine by AWETA with ULTRAVISION sensor was used to sort fruit by calibre size and coverage with red overcolour. Fruit calibre sizes were displayed in 5 mm increments. Fruit red overcolour was measured as weighted average of percentage of skin surface of each fruit covered red and the intensity of that colour. According to that scheme, each fruit was assigned one of five colour classes (0-20 % red, 20-40 % red, 40-60 % red, 60-80 % red or 80-100 % red) by the sorting machine. Additional human intervention while sorting was needed to separate fruit with skin defects to determine the amount of fruit lost to cider grade.

Results

Flowering intensity. In 2023, the average flowering intensity of the AV treatments was slightly lower for all cultivars than in the control but remained within the target range [Fig. 2]. In the second yield year, 2024, the flowering intensity in the AV treatments was again slightly lower in the control treatment for all cultivars [Fig. 3]. In addition, the differences between the cultivars were more pronounced than in the previous year. For ‘Freya®’ and ‘Delcored®’, the average flowering intensity of the AV treatments remained about one rating point below the control value and thus below the target range. Furthermore, flowering was more unequal in these cultivars, i.e. the differences between individual trees were larger than for ‘Topaz’ and ‘Natyra®’.

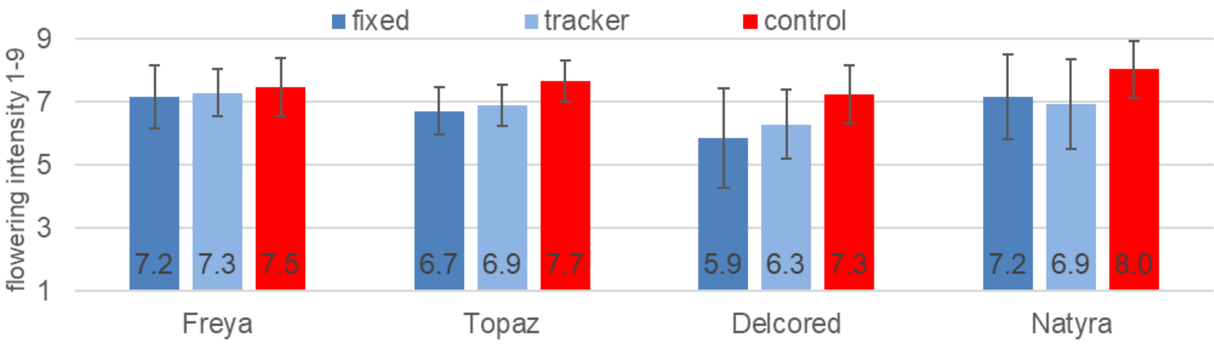

Figure 2: Flowering intensity in 2023 on scale 1-9 with 1 = no flowers to 9 = white bloom. Average of N = 80 trees/treatment and standard deviation.

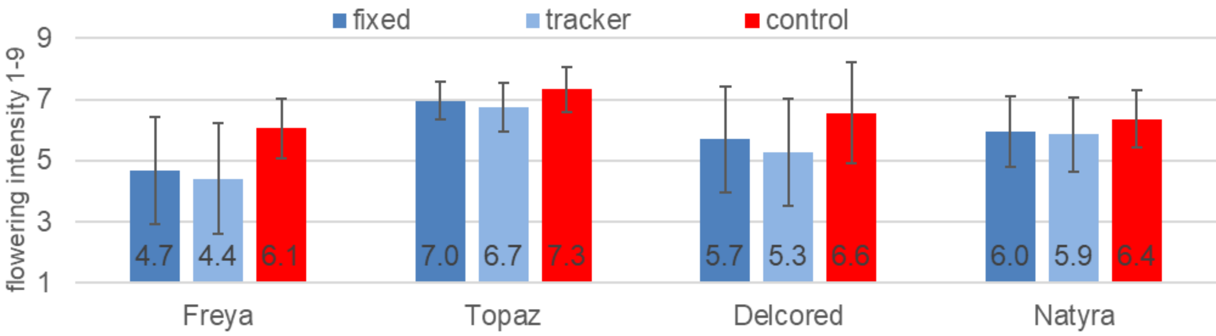

Figure 3: Flowering intensity in 2024 on scale 1-9 with 1 = no flowers to 9 = white bloom. Average of N = 80 trees/treatment and standard deviation.

Number of pickings. In the case of ‘Freya®’, ‘Topaz’ and ‘Natyra®’, delayed overcolour development was observed in the AV treatments in both trial years. Thus, most fruit in the control were harvested at the first picking. Figures 4 and 5 give the percentages of fruit harvested at each picking in 2023 and 2024, respectively. In both AV treatments, most fruit were taken at the second picking.

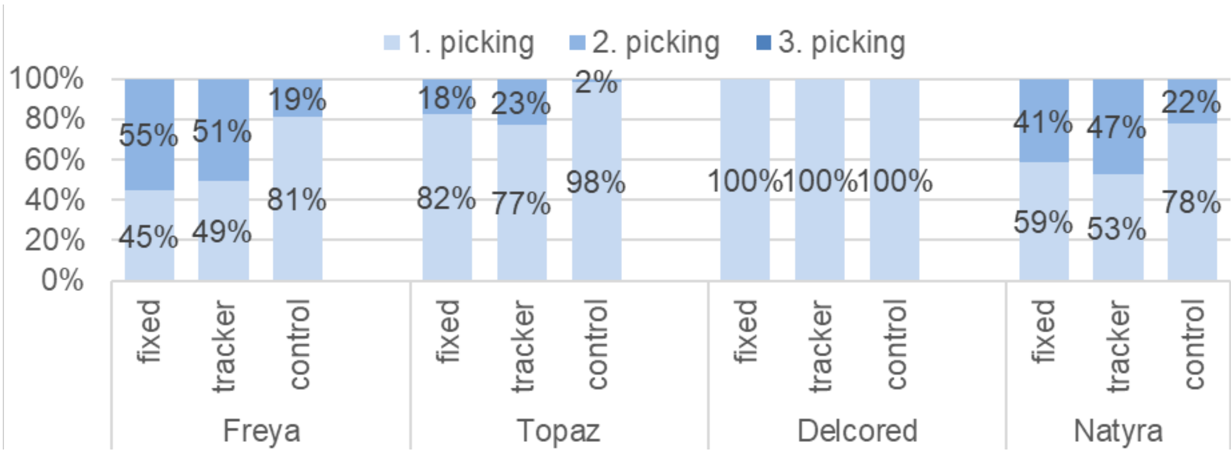

Figure 4: Percentage of fruit harvested per picking in 2023. N = 80 trees/treatment.

Time between pickings varied between 7 and 14 days. For ‘Freya®’, even a third picking was necessary in 2024. ‘Delcored®’, given its uniform red overcolour, was harvested in a single pass for all treatments.

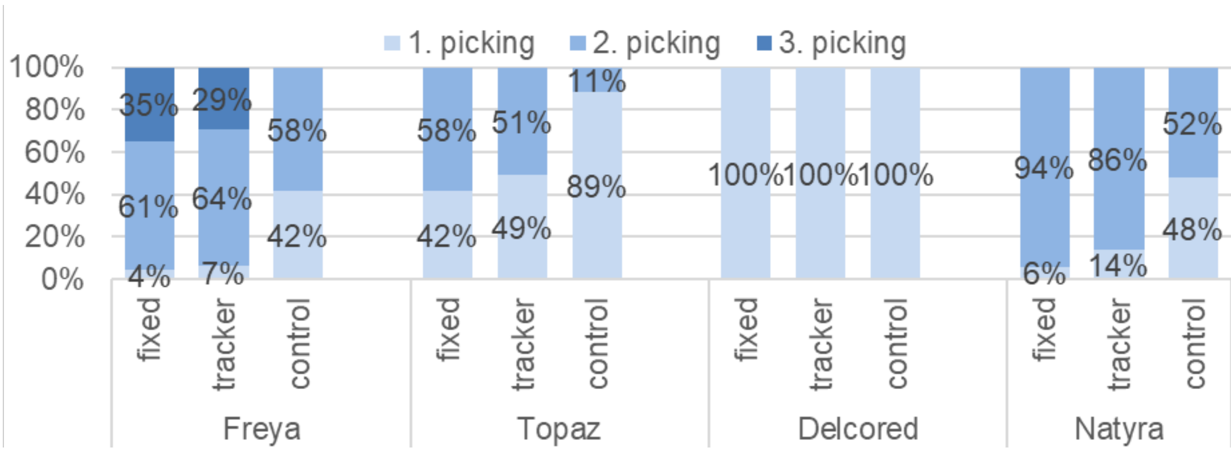

Figure 5: Percentage of fruit harvested per picking in 2024. N = 80 trees/treatment.

Yield. In 2023, average yields differed little among treatments, whereas in 2024 the control consistently outperformed both AV treatments [Fig. 6].

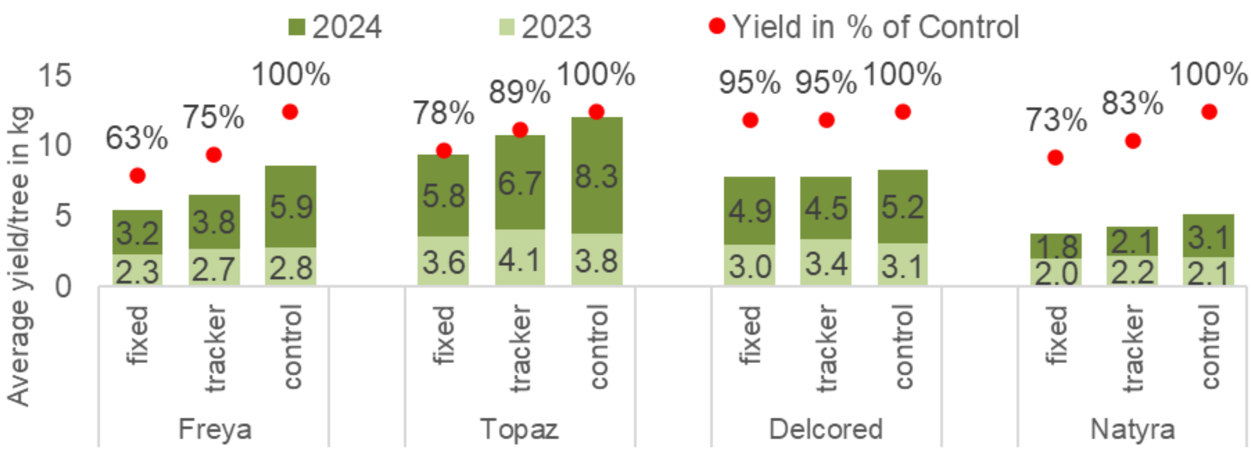

Figure 6: Average yield per tree in 2023 and 2024 in kg and cumulated yield in AV treatments expressed as percentage of yield of control. N = 80 trees/treatment.

In most cases, the tracker treatment achieved higher yields than the fixed-tilt treatment. Summed up over the two years, the cumulative yields were lower in the AV treatments, with the sharpest decline recorded for ‘Freya®’ with 63% of the control for the “fixed” treatment. ‘Topaz’ achieved the highest absolute cumulative yields of the four cultivars, while ‘Delcored®’ showed the most stable performance of the AV treatments with yields of 95% of the control. For ‘Natyra®’, the percentual yield losses in the AV treatments were comparable to ‘Freya®’ and ‘Topaz’, but the absolute yields were the lowest of all cultivars. Yield data broken down into fruit lost to processing grade (cider) and table fruit is given in Figure 7.

Figure 7: Average yield per tree in 2023 and 2024 in kg divided into table fruit and cider fruit. N = 80 trees/treatment.

Fruit Size. Calibre sizes are given in 5 mm increments for 2023 and 2024, respectively [Fig. 8 and 9]. The range of 65 to 85 mm is marked in shades of green for better orientation, reflecting the assumption that fruit within this range is usually marketable without a price markdown. The data demonstrates a tendency towards smaller fruit in AV treatments, which could be problematic for some cultivars but advantageous for others. For instance, in 2023, 30% of ‘Freya®’ fruits in the control exceeded 90 mm and were thus oversized, compared to only 13% in the fixed treatment. ‘Topaz’ consistently achieved the highest proportion of fruits within the target range of 65-85 mm. Differences in ‘Delcored®’ fruit size across treatments were comparatively small. 'Natyra' produced relatively small fruits in 2023, but most of them were within the marketable range. In the following year, however, the proportion of fruits smaller than 65 mm was over 70% in the fixed treatment and still high with 20% in the control.

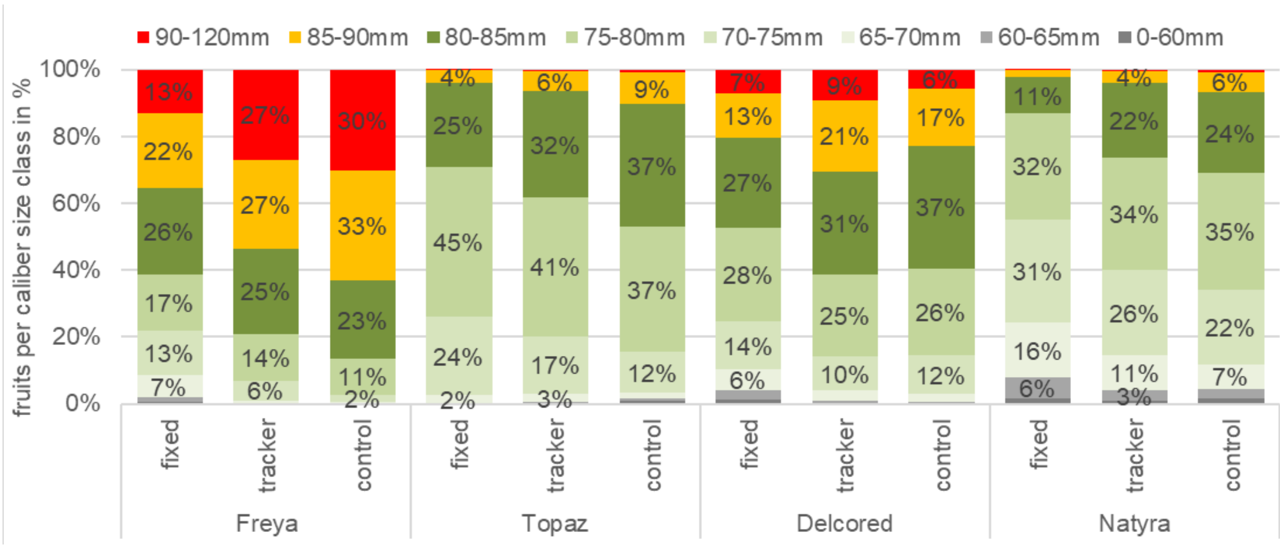

Figure 8: Yield 2023. Percentage of harvested fruits per calibre size class. Sum of all pickings.

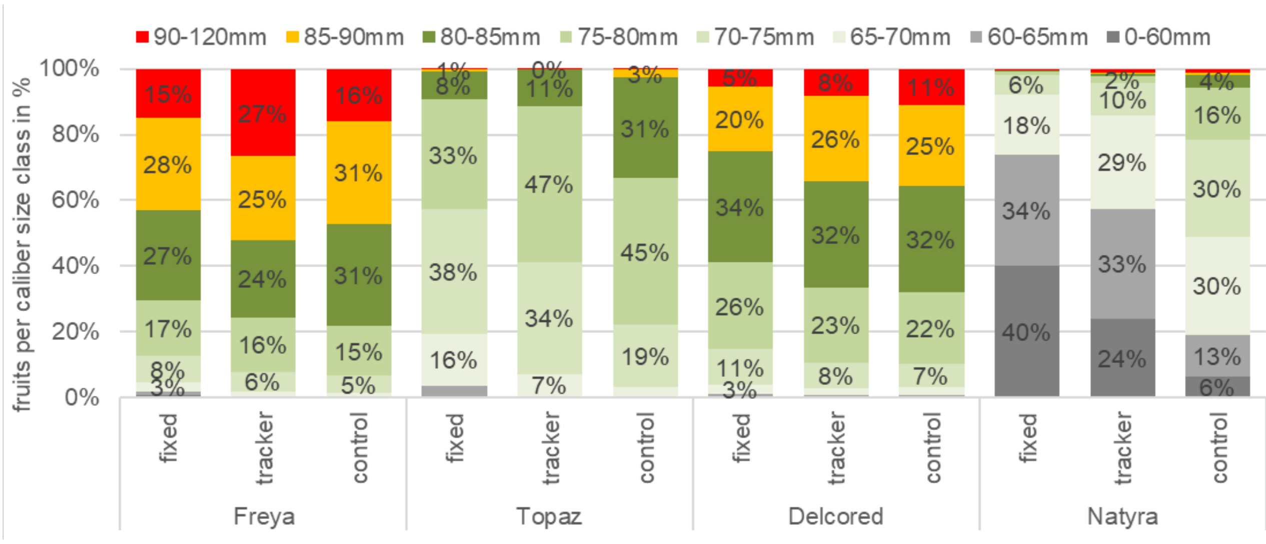

Figure 9: Yield 2024. Percentage of harvested fruits per calibre size class. Sum of all pickings.

Fruit overcolour. Despite later harvest dates, fruit red overcolour (or "redness") remained consistently lower in AV treatments. This effect was identifiable to varying degrees for all cultivars and both years [Fig. 10 and 11].

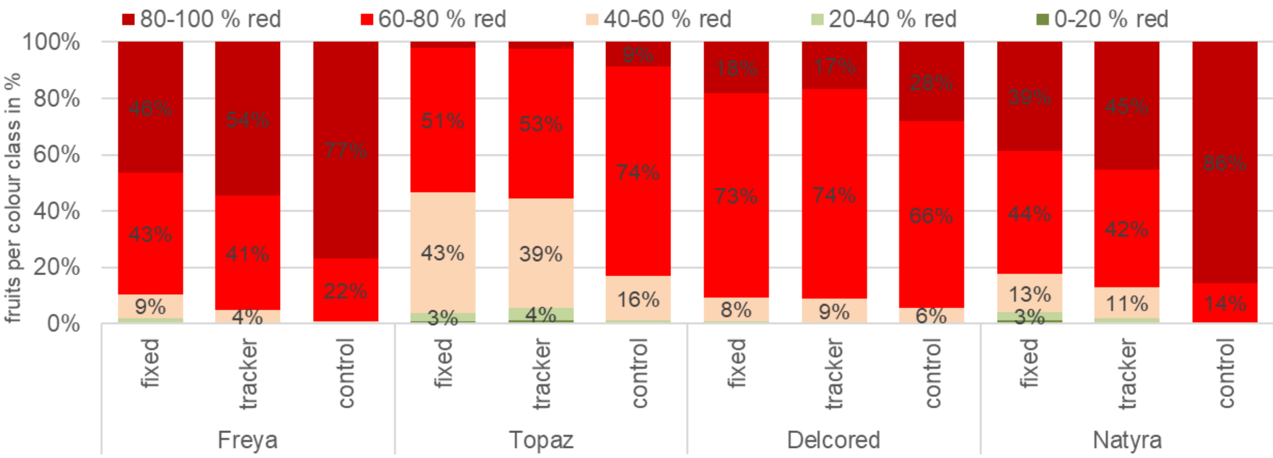

Figure 10: Percentage of fruits in five overcolour classes 2023.

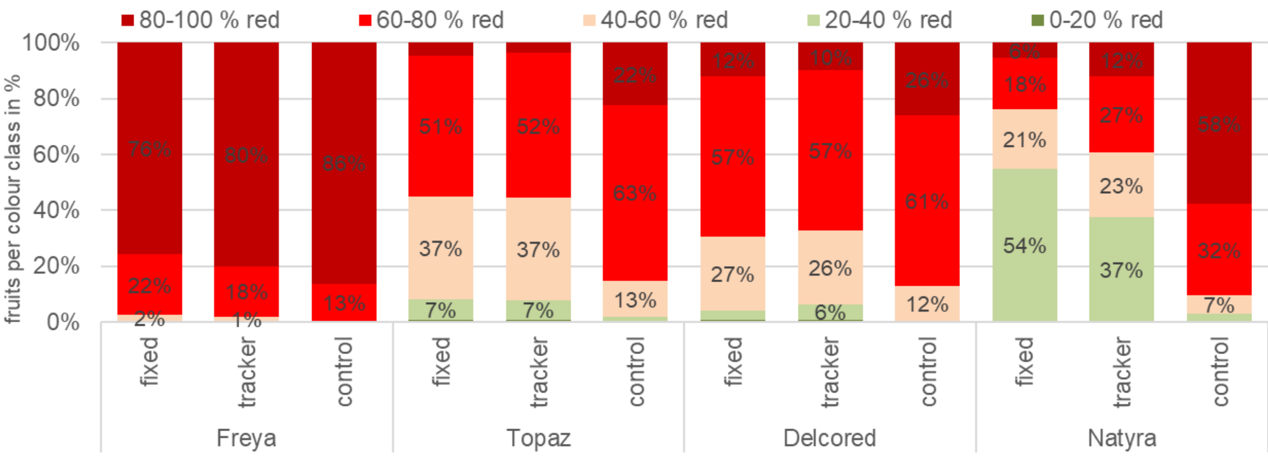

Figure 11: Percentage of fruits in five overcolour classes 2024.

For example, for ‘Topaz’ in 2023 the percentage of harvested fruits with a redness of 60 to 80 % of their surface was 51 % in the fixed treatment, but 74 % in the control. For ‘Natyra®’ in 2024, 90 % of the harvested fruits in the control had a redness of 60 % or more (32 % covered red 60-80 % of their surface plus 58 % covered red 80-100 % of their surface). In the fixed treatment, only 24 % (18 % plus 6 %) of fruits showed a redness of 60 % or more. Compared to that, the data shows less effect of AV treatments on overcolour development for ‘Freya®’ in both years and ‘Delcored®’ in 2023.

Discussion

When interpreting the results, it should be considered that the trees are still young and have not yet reached their maximum yield and crown volume. For three of the four cultivars, the “tracker” treatment has so far returned higher yields than the treatment “fixed”. This might be partly caused by the delay of panel installation in 2022 mentioned above.

Flowering intensity in AV treatments tended to be weaker in the second year of the trial, although this was not observed to the same extent for all cultivars. ‘Freya®’ showed the sharpest decline in flowering intensity in the AV treatments in 2024 compared to the control with a lower corresponding yield in AV treatments, without this being explained by an excessive fruit load in the first year.

During the period observed, the yield in AV treatments remained lower than in the control for all cultivars, which was partly due to a smaller average fruit size. 'Topaz' reached the highest yields, even though yield in the two AV treatments was reduced to 78% and 89% of the yield of the control, respectively. The overall yield level of ‘Delcored®’ was slightly lower compared to 'Topaz', but with 95% of control yield in both AV treatments, ‘Delcored®’ appeared least affected by agrivoltaics growing conditions. For ‘Natyra®’, the general trend towards yield losses in the AV treatments was evident as well, but furthermore, even the two-year cumulative yield in the control fell short of expectations at 5.2 kg per tree without apparent reasons.

Given a harvest decision based on visual ripeness of the fruit, the main harvest date was delayed by about 1-2 weeks for the cultivars ‘Topaz’, ‘Freya®’ and ‘Natyra®’ in both AV systems tested. The uniform red overcolour of ‘Delcored®’ proofed to be advantageous in the agrivoltaics context from our view, because it simplified harvest decision and picking.

Despite the mostly delayed harvest date, overcolour development remained reduced in AV treatments and led to varying degrees of loss of table fruit depending on the cultivar. As market expectations about the degree of redness of an apple are cultivar-specific, the colour data recorded by the sorting machine does not reflect marketability one-to-one. Causes of fruit loss to cider grade are not shown in this paper, but results indicated that loss of fruit in AV treatments was mainly due to insufficient size and poor red colour, while losses in the control were mainly due to infestation with sooty blotch and, for ‘Freya®’ in 2024, calibre size above 90 mm. ‘Natyra®’ returned an amount of cider fruit in 2024 being far too high in both AV treatments as well as in the control.

Given the wide range of results between the cultivars tested, the selection of suitable cultivars for agrivoltaic production appears to be of crucial importance in the future.

Acknowledgements

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