Agrivoltaic trial preparation

Understanding spatial vineyard variability of cv. Viosinho at Instituto Superior de Agronomia

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Dissertation to obtain the Master's Degree in

Engenharia de Viticultura e Enologia

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Year 2023

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Abstract

Climate change threatens agriculture, particularly vine cultivation for wine production, with extreme heat, droughts, and erratic rainfall affecting harvest planning, increasing disease risks, and degrading grape quality. One promising option is the use of photovoltaic panels in agrivoltaic setups. These panels provide shade, reducing light exposure, lowering temperatures, and conserving water in vineyards furthermore they offer a means to mitigate the impacts of climate change on viticulture while fostering sustainability and providing farmers an extra source of income. This study aims to achieve two primary objectives: firstly, to assess the spatial variability within the vineyard and identify optimal locations for study plants, ensuring fair comparisons between treatments; and secondly, to comprehensively characterize the initial year of the experiment prior to implementing the agrivoltaic system. Focused on Viosinho white grape, this study was carried out in a Lisbon experimental vineyard (ISA). Given that the placement of the agrivoltaic structure was predetermined within a single large parcel of the vineyard, an initial investigation was conducted to identify plants outside this designated area that exhibited comparable performance. Subsequently, two distinct plots were established: the control plot and the agrivoltaic plot. In this thesis, various parameters were systematically gathered to characterize the selected plants throughout the research, such as: shoot length, phenology, water status, leaf areas, thermography, yield components, berry composition and wine analysis, among others. Statistical tests for data comparison included ANOVA and Tukey Test.

The study found that phenology development was closely aligned for both plots, except during March's budburst, with the PV plot being bursting slightly later than the control plot. Vegetative parameters evolved similarly, averaging 2.85 m^2 of leaf area near harvest for both plots. Stem water potential showed no differences except at the pea-size stage, where the PV plot presented average values 15% lower than the control plot, but both maintaining comfort water status until veraison. Photosynthesis activity showed statistically different values between the two plots, exclusively at veraison, where the PV presented 23% less photosynthetic activity than the Control. Regarding stomatal conductance, no statistical differences were found between plots except at maturation, with 40% more activity for Control compared to the PV. Bird activity affected PV plot significantly more than the Control plot, eating 3 times more bunches in the PV, however not significantly affecting the final yield. Oenological parameters (alcohol content, pH, and total acidity) showed no significant differences.

In conclusion, both plots exhibited similar physiological and oenological characteristics, with slight variations in plant water status and initial phenological stages. This suggests the chosen smart points are suitable for assessing the future impact of solar panels, providing a foundation for further agrivoltaic research, emphasizing the significance of accounting for spatial variability in the field. However, it should be noted for future reference, that the PV plot has a trend to be slightly more stressed than the Control plot, even though in most phenological stages the difference is not statistically significant. Ongoing research and long-term monitoring will yield valuable insights for optimizing the coexistence of solar energy production and vineyard cultivation. Moreover, it is advisable to explore the critical phenological periods to strike the best balance between energy production, ideal plant growth conditions, and overall wine quality.

Keywords: Climate change, Solar panels, Grapevine, Sustainability, Advanced Technologies

Sumario

As alterações climáticas ameaçam a agricultura, especialmente a cultura da vinha para a produção de vinho, com o calor extremo, as secas e as chuvas erráticas afetando o planeamento da colheita, aumentando os riscos de doenças e degradando a qualidade da uva. Uma opção promissora é o uso de painéis fotovoltaicos em sistemas agrivoltaicos. Estes painéis fornecem sombra, reduzindo a exposição à luz, diminuindo as temperaturas e conservando água nas vinhas; além disso, oferecem um meio de mitigar os impactos das alterações climáticas na viticultura, ao mesmo tempo que promovem a sustentabilidade e proporcionam aos agricultores uma fonte extra de renda. Este estudo tem como objetivo alcançar dois objetivos principais: primeiro, avaliar a variabilidade espacial dentro da vinha e identificar locais ótimos para as plantas do estudo, garantindo comparações justas entre os tratamentos; e segundo, caracterizar de forma abrangente o primeiro ano do experimento antes de implementar o sistema agrivoltaico. Focado na uva branca Viosinho, este estudo foi realizado numa vinha experimental em Lisboa (ISA). Dado que a colocação da estrutura agrivoltaica estar predefinida dentro de uma única grande parcela da vinha, foi realizada uma investigação inicial para identificar plantas fora desta área que exibiam um desempenho comparável. Posteriormente, foram estabelecidas duas parcelas distintas: a parcela de controlo e a parcela agrivoltaica. Ao longo desta tese foram recolhidos diversos parâmetros para caracterizar as plantas selecionadas, tais como: comprimento dos sarmentos, fenologia, estado hídrico, áreas foliares, termografia, componentes de produção, composição dos bagos e análise do vinho, entre outros. Os testes estatísticos para comparação de dados incluíram ANOVA e Teste de Tukey. O estudo constatou que o desenvolvimento da fenologia estava alinhado de forma semelhante para ambas as parcelas, exceto durante o abrolhamento de março, com um ligeiro atraso na parcela fotovoltaica. Os parâmetros vegetativos evoluíram de forma semelhante, com uma média de 2,85 m^2 de área foliar perto da vindima para ambas as parcelas. O potencial hídrico do caule não apresentou diferenças, exceto na fase de bago de ervilha, onde a parcela agrivoltaica apresentou valores médios 15% inferiores à parcela de controlo, mas ambas mantiveram um estado hídrico confortável até ao pintor. A atividade fotossintética apresentou diferenças significativas entre as duas parcelas exclusivamente ao pintor, , neste caso, a parcela agrivoltaica apresentou uma atividade fotossintética 23% inferior à parcela controlo. Relativamente à condutância estomática, não foram encontradas diferenças significativas entre parcelas, com excepção da fase final da maturação, onde a parcela controlo apresentou valores cerca de 40% superiores à parcela agrivolaica. A atividade dos pássaros afetou significativamente a parcela agrivoltaica mais do que a parcela controlo, destruindo três vezes mais bagos na parcela agrivoltaica, no entanto, não afetando significativamente o rendimento final. Os parâmetros enológicos (teor alcoólico, pH e acidez total) não apresentaram diferenças significativas. Em conclusão, ambas as parcelas exibiram características fisiológicas e enológicas semelhantes, com ligeiras variações no estado hídrico das plantas e nos estágios fenológicos iniciais. Este facto sugere que as plantas de estudo escolhidas são adequados para avaliar o impacto futuro dos painéis solares, fornecendo uma base para futuras pesquisas agrivoltaicas e enfatizando a importância de considerar a variabilidade espacial no campo. No entanto, é importante constatar para referência futura que a parcela agrivoltaica apresentou uma tendência a estar em estados de stress ligeiramente superiores à parcela de controlo, mesmo que na maioria dos estados fenológicos, a diferença não tenha sido estatisticamente significativa. No futuro, a monitorização a longo prazo, após instalação dos painéis, proporcionará *insights* valiosos para otimizar a coexistência da produção de energia solar e o cultivo de vinha. Além disso, é aconselhável explorar os períodos fenológicos críticos para alcançar o melhor equilíbrio entre a produção de energia, as condições ideais de crescimento das plantas e a qualidade geral do vinho.

Palavras-chave: Mudanças climáticas, Painéis solares, Videira, Sustentabilidade, Tecnologias avançadas

Sumário alargado

As alterações climáticas são cada vez mais uma ameaça para a agricultura, incluindo o cultivo de uvas de mesa e para a produção de vinho. As consequências destas alterações manifestam-se principalmente através de ondas de calor e secas e precipitações erráticas. Estes acontecimentos influenciam diretamente o planeamento da vindima, aumenta os riscos de doenças e diminui a qualidade das uvas. Entre as várias soluções possíveis, tais como modificar práticas agronómicas e realocar áreas de cultivo, uma opção promissora poderá ser a utilização de painéis fotovoltaicos sobre as próprias culturas, um sistema conhecido como agrivoltaico. Os painéis fornecem sombra, reduzindo a exposição à luz, diminuindo as temperaturas e promovendo uma maior eficiência no uso da água na vinha. Além disso, oferecem uma forma de mitigar os impactos das alterações climáticas na viticultura, promovendo a sustentabilidade energética e fornecendo aos agricultores uma fonte extra de rendimento. Este estudo tem como objetivo alcançar dois objetivos principais: primeiro, avaliar a variabilidade espacial dentro da vinha e identificar locais ótimos para as plantas do estudo, garantindo comparações justas entre os tratamentos; e segundo, caracterizar de forma abrangente o primeiro ano do experimento antes de implementar o sistema agrivoltaico. O presente estudo focou na variedade de uva branca Viosinho e foi conduzido numa vinha experimental no campus agrícola de Lisboa (ISA). A extensa recolha de dados abrangeu a determinação da fenologia, análise do solo e do estado nutricional das plantas através de análises dos pecíolos foliares, comprimento dos sarmentos, áreas foliares (total e exposta), porosidade da sebe, estado hídrico da planta (através de potencial hídrico do caule e condutância estomática), termografia e componentes de rendimento (tais como o número de cachos e o rendimento total). As análises detalhadas pré-colheita incluíram a determinação das características do cacho, como número de bagos, comprimento e número de ramificações do pedúnculo e peso médio do cacho. Por fim, foram realizadas análises do mosto e do vinho, como pH, sólidos solúveis totais e acidez total. Os testes estatísticos para comparação de dados incluíram ANOVA e Teste de Tukey. O estudo constatou que o desenvolvimento da fenologia estava alinhado de forma semelhante para ambas as parcelas, exceto durante o abrolhamento, em março, com um ligeiro atraso na parcela fotovoltaica. Os parâmetros vegetativos evoluíram de forma semelhante, com uma média de 2,85 m^2 de área foliar perto da vindima para ambas as parcelas. O potencial hídrico do caule não apresentou diferenças, exceto na fase de bago de ervilha, onde a parcela agrivoltaica apresentou valores médios 15% inferiores à parcela de controlo, mas ambas mantiveram um estado hídrico confortável até ao pintor. A atividade fotossintética apresentou diferenças significativas entre as duas parcelas exclusivamente ao pintor, , neste caso, a parcela agrivoltaica apresentou uma atividade fotossintética 23% inferior à parcela controlo. Relativamente à condutância estomática, não foram encontradas diferenças significativas entre parcelas, com excepção da fase final da maturação, onde a parcela controlo apresentou valores cerca de 40% superiores à parcela agrivolaica. A atividade dos pássaros afetou significativamente a parcela agrivoltaica mais do que a parcela controlo, destruindo três vezes mais bagos na parcela agrivoltaica, no entanto, não afetando significativamente o rendimento final.. Os parâmetros enológicos (açúcares, teor alcoólico, pH e acidez total) não mostraram diferenças evidentes, destacando ainda que os vinhos finais produzidos também foram muito homogéneos. Em geral, espera-se que os painéis solares influenciem significativamente esses parâmetros nas próximas vindimas, por meio de modificações estatisticamente significativas em quase todos os parâmetros na parcela PV. Em conclusão, ambas as parcelas exibiram características fisiológicas e enológicas semelhantes, com ligeiras variações no estado hídrico das plantas e nos estágios fenológicos iniciais. Este facto sugere que as plantas de estudo escolhidas são adequados para avaliar o impacto futuro dos painéis solares, fornecendo uma base para futuras pesquisas agrivoltaicas e enfatizando a importância de considerar a variabilidade espacial no campo. No entanto, é importante constatar para referência futura que a parcela agrivoltaica apresentou uma tendência a estar em estados de stress ligeiramente superiores à parcela de controlo, mesmo que na maioria dos estados fenológicos, a diferença não tenha sido estatisticamente significativa. No futuro, a monitorização a longo prazo, após instalação dos painéis, proporcionará *insights* valiosos para otimizar a coexistência da produção de energia solar e o cultivo de vinha. Além disso, é aconselhável explorar os períodos fenológicos críticos para alcançar o melhor equilíbrio entre a produção de energia, as condições ideais de crescimento das plantas e a qualidade geral do vinho.

Palavras-chave: Mudanças climáticas, Painéis solares, Videira, Sustentabilidade, Tecnologias avançadas

1 Introduction

Climate change is a global challenge that requires concrete solutions in all sectors, including agriculture. Vine cultivation, which is crucial for wine production, is particularly affected by climate impacts, putting the sustainability and productivity of the wine sector at risk. The effects of climate change manifest themselves through phenomena such as prolonged periods of heat, more frequent droughts, and irregular rainfall. These climate changes directly affect vine cultivation, making harvest planning more complex, increasing the risk of plant diseases, and compromising grape ripening and quality. To ensure the continuity of viticulture in a context of climate change, innovative and sustainable solutions are needed (Leeuwen & Darriet, 2016; Mosedale et al., 2016; van Leeuwen et al., 2019).

Among possible solutions, photovoltaic panels present a promising option in an agrivoltaic scenario. This innovative technology involves covering the crops to a height of approximately 4 meters while respecting the distances between the rows. Photovoltaic panels efficiently convert solar energy into clean, renewable electricity, offering several significant advantages for agriculture. Firstly, their use drastically reduces greenhouse gas emissions, actively contributing to the fight against global warming. This transition to a sustainable energy supply is crucial to mitigate the impacts of climate change on viticulture and to protect the environment. Photovoltaic panels also offer energy autonomy to winegrowers. Power generation through photovoltaic panels reduces or even eliminates electricity-related operating costs and ensures a reliable and clean energy supply for agricultural activities directly in the field. This is especially important in times of drought when the irrigation of vines requires a stable energy source to maintain plant health and grape quality. In addition, in an agrivoltaic scenario, the panels offer the possibility of creating a shaded area, thus reducing the amount of light hitting the plants. In this way, their application allows both temperature and water consumption to be lowered, with additional savings in hot, dry growing areas that are subject to irrigation. In this scenario, they could reduce the consequences of extreme climatic events, such as cluster burning or leaf necrosis, allowing yields to be preserved and vines to be grown in new areas, or at least to preserve those in which plants are already present (Ferrara et al., 2023). Another key aspect of photovoltaic panels is their flexibility in installation. They can be placed on unused land or integrated into existing agricultural structures, allowing efficient use of available space. This versatility offers farmers the opportunity to maximise renewable energy production without compromising the main agricultural activity. The combination of sustainable farming practices and the use of photovoltaic panels is a winning strategy to address the effects of climate change on viticulture. Adopting these innovative solutions allows farmers to mitigate negative impacts, reduce dependence on traditional energy sources and promote sustainable wine production (Ise, 2022; Malu et al., 2017; Mamun et al., 2022; Santos et al., 2020).

1.1 Aims

Initially the purpose of this study was to compare the performance of vines under the photovoltaic panels (PVs) with a control plot. However, for reasons that go beyond the team's possibilities, the installation of the PVs was postponed one year. A new objective was defined, to ensure a fair comparison between PV and control plants once the panels were installed. As such, the objective of this study is to thoroughly analyse the initial year (year 0) of an agrivoltaic experiment to determine if there are any statistical variations between the study areas (control and PV-treated) and be prepared for these differences, if any, once the panels are up. The main objective of this thesis can be separated into the following two topics:

- Assess Vineyard Spatial Variability: The first objective is to evaluate the spatial variability within the vineyard, enabling the selection of suitable sentinel plants for an accurate representation of the vineyard plots selected for the future installation of the agrivoltaic panels field experiment. By carefully considering the vineyard's variations, it is possible to ensure that representative plants are chosen for a comprehensive analysis.
- Characterize Year zero of the agrivoltaic experiment: The second objective is to fully characterize the initial year of the experiment and examine potential statistical differences between the study plots: control and the plot where PVs will be installed (PV-treated). This characterization involves assessing several parameters, including soil chemical and physical composition, plant vegetative and phenological development, plant and soil water status, plant physiological status, yield, grape composition, and other relevant factors. These comprehensive evaluations will provide valuable insights into the future overall impact of solar panels on the grapevines.

By achieving these objectives and considering various parameters, the aim is to gain a holistic understanding of spatial variability regarding grapevine growth and productivity of the vineyard plot where the agrivoltaic trial will be installed. This research will contribute to a broader understanding of sustainable vineyard practices and guide future decision-making in vineyard management.

2 Literature review

2.1 Climate change and renewable energy

In this century our society is fighting one of the greatest challenges in our history, climate change, which manifests itself through rising temperatures and many other effects. Its main cause is the increase in the amount of greenhouse gases, such as CO_2 and NO_2, in the atmosphere, which is closely linked to our lifestyle, and in particular to the ways in which energy is obtained and used. Energy is generally obtained by burning oil, coal, which inevitably releases greenhouse gases (IPCC, 2014).

In the atmosphere, greenhouse gases have various interactions, but in particular, they redirect solar energy emitted by the Earth towards the Earth itself, creating the greenhouse effect. As a result, our world is less able to reduce heat, which results in an increase in the temperature of the Earth and oceans, as well as reducing the total area covered by ice, which has the greatest capacity to reflect solar radiation (IPCC, 2014).

These facts lead to changes in atmospheric balances and ocean currents, which consequently increase the rate of extreme events, such as heavy rainfall, storms, tornadoes, droughts. They also create an imbalance of the seasons, which leads to changes in all cycles of flora and fauna. Of particular relevance are obviously plants, which do not have the capacity to move, and microorganisms, which are fundamental in making nutrients available through the decomposition of organic matter (IPCC, 2014; Bartolini et al., 2008). From an agriculture point of view, these phenomena increase the difficulties of yield stability, quality, disease, and insect control, with devastating effects in our lives.

Adding to the complexity and severity of the situation, our planet also faces pollution from chemicals and plastics, including microplastics, which disrupt biological systems and increase the risks of cancer and poisoning. The use of chemical herbicides, fungicides, and insecticides in agriculture contributes to soil degradation and negatively impacts various organisms, including microorganisms and insects (IPCC, 2014). The implications of climate change in agriculture, more specifically for viticulture, are presented in the next chapter but already from this framework it’s possible to extrapolate some possible solutions to hinder all these processes. Addressing climate change and its impacts on agriculture, including viticulture, requires implementing solutions to mitigate these processes. The transition to green energy, particularly through the adoption of renewable sources like photovoltaic panels, plays a vital role in this endeavour. During this century the research in this field increased exponentially. Thanks to the photovoltaic effect, these panels can harness energy from the sun and convert it directly into usable electricity. At the core of a photovoltaic panel are photovoltaic cells, made from semiconductor materials such as silicon. When photons from sunlight strike the surface of the cells, they shake the electrons in the semiconductor material, generating a charge separation that leads to the creation of an electric current. It is important to note that solar panels do not require direct sunlight to work effectively. Even diffuse or indirect light can provide sufficient energy for electricity generation, albeit at a lower efficiency than direct sunlight. Inside the photovoltaic panel, photovoltaic cells are interconnected and equipped with electrical contacts. These contacts allow the electrical current generated by the cells to be collected and channelled to the outside, where it can be used to power electrical equipment or stored in batteries for future use. The efficiency of photovoltaic panels depends on several factors, such as the quality of the photovoltaic cells, the technology used, and the intensity of sunlight (Barron-Gafford et al., 2019; Dinesh & Pearce, 2016). As a result, the energy produced by photovoltaic panels is clean, renewable and has a low environmental impact. It contributes, in this way, to the reduction of carbon emissions, thus combating climate change (Gorjian et al., 2022; Mamun et al., 2022). It is estimated that aerial farms can have an energy production capacity of between 500 and 800 kWp (kilowatt peak) per hectare. This means that, on average, they produce less energy per unit area than conventional ground-mounted photovoltaic systems, which can reach a capacity of 700-1,100 kWp per hectare, depending on the type of installation. On the other hand, interspaced agrivoltaic systems, which manage intercropped crops between solar panels, require even more space. These systems can handle 250 to 400 kWp per hectare, implying that they require approximately three times more land than ground-mounted PV systems. It is important to consider that the choice between the different types of systems depends on many factors, such as land availability, local agricultural needs and the main objective of the installation. This amount of energy can also greatly help companies in differentiating expenses and revenues (Ise, 2022).

2.2 Climate change in viticulture

Today, temperature has increased, compared to pre-industrial levels (early IX century), by + 0.98°C on average, but the increase during general grapevine growing season, from May to September for the northern hemisphere, is greater (around 2.3 to 5.3°C), with a sharp decrease in the incidence of precipitation (Fraga et al., 2012; Santos et al., 2020). This fact could and will have great effects on viticulture, especially considering that the world's main viticultural regions are located at specific latitudes, such as between the 35th and 50th parallels in the northern hemisphere and between the 30th and 45th in the southern hemisphere (Fraga et al., 2012; van Leeuwen et al., 2019). In fact, the main areas of grape production are Europe, including France, Italy, Spain, and Portugal, which develop the vast majority of world production, the United States, whose main winegrowing regions are in California, and in the southern hemisphere the main exponents are Australia, South Africa and New Zealand. In addition, there are some emerging countries in both hemispheres, including China, Chile, and

Brazil. Consequently, as it’s possible to imagine, changing temperatures, especially in the Northern Hemisphere, could force winegrowers to make huge changes to adapt their plants to the new climatic conditions, with very high costs for companies and very serious consequences for the global market (Fraga et al., 2012; Santos et al., 2020; van Leeuwen et al., 2019). In particular, the effects of these practices will affect the growing period of the grapes, which will be brought forward by several days, creating an imbalance in phenology, in the harvest period and consequently ripening compounds. These facts also expose grapes to others greater risks: during bud break they could be more affected by late frosts, which could damage young shoots, with high damage to production; or there could be irregular ripening phenomena, affecting in particular the final part of the ripening season, with grapes having higher sugar content compared to the ripening of phenols and aromas; or even do not ripen at all as a consequence of lack of water and high temperatures (Fraga et al., 2012; Leeuwen & Darriet, 2016; Mosedale et al., 2016; Santos et al., 2020).

It is also generally accepted that it is very difficult to have high quality and good yields in tropical areas. Therefore, the only options available is to adapt vine cultivation as best as possible with agronomic and cultural strategies, and those of changing the location and areas of cultivation, in altitude and latitude towards the north. This fact also gives the possibility of obtaining other areas for wine production, although there are other factors to consider besides temperatures, such as soil types and consequently the adaptability of varieties (Droulia & Charalampopoulos, 2021; van Leeuwen et al., 2019). As mentioned in the previous chapter, some possible solutions involve the use of modern technologies to assess and better control production, quality, and plant health. One of these is the implementation of agrivoltaic systems, through the use of solar panels over crops, in order to reduce the negative effects of climate change. In general, it is well established that this type of system can largely help to lower the temperature of the microclimate of the vineyard, the soil and the panels themselves, enabling better performance. In fact, Mamun et al., (2022) show how in the agrivoltaic system the temperature can be 8.9° lower than in a normal photovoltaic park, increasing energy production performance by about 27%. Lowering vine microclimate temperature preserves grape acidity, making agrivoltaic applications particularly important for white and sparkling wines. Shading also decreases the loss of water, thus increasing the efficiency of utilisation, allowing savings from an irrigation point of view. In addition, it increases and differentiates the overall turnover of companies, also giving the possibility to have usable energy in the fields, for tractors or for the use of other technology such as irrigation systems or soil water probes. Besides this, it is also a non-polluting technology, as far as its specific use is concerned (Dinesh & Pearce, 2016; Gorjian et al., 2022; Malu et al., 2017).

2.3 Influence of temperature changes on grapevine growing and grape maturation

It is well known that vines grow best in temperate zones with good temperature fluctuations throughout the year, but obviously they must also grow in a suitable environment that maintains the right seasonal temperatures. During winter, vines are in a particular condition called dormancy, which serves to overcome this season and prepare the plant for spring; to break this state they need cold, obviously avoiding temperatures that are too low so as not to damage the trunk (Bucur & Dejeu, 2020). Studies and field experience show that grapevines need temperatures below around 4º C, for at least 15 days in total, in order to degrade ABA (abscisic acid), stored in the buds, which has an inhibiting effect on budding. This interrupts the dormancy phase and consequently, when the soil temperature starts to rise above 7º C on average, the vines begin to acquire water and nutrients from the soil. (Zheng et al., 2018). When the air temperature starts to rise above 7º C on average, grapevines use these reserves and those stored in the vacuoles of the parenchyma cells of the woody trunk for the year's budding and growth (Mattern, s.d.-a; Moncur et al., 1989; Oliveira, 1998; Parker et al., 2011). If budburst occurs too early, due to too high average temperatures in spring, plants risk being exposed to late frosts, which could irreparably damage new shoots and a large percentage of the final yield (Sgubin et al., 2018).

After the budding period, and thus during the vegetative season, vines need higher temperatures. For flowering they need an average of 10° C, and 20-30° C for the ripening period; some studies confirm that temperature fluctuation is also important for photosynthetic activity, with a close correlation to the storage capacity of carbohydrates, the synthesis and storage of important metabolites such as anthocyanins, polyphenols and aromas (Tombesi et al., 2019).

The ideal fluctuation is 10-15° C between day and night. In general, depending on the variety and the commercial purpose of each farmer, ideal temperatures for ripening are around 25-30° C during the day and 15-20° C during the night (Gaiotti et al., 2018). Therefore, temperatures above or below these values decrease overall plant photosynthetic rate and thus have an impact on ripening, which consequently affects wine quality (Pastore et al., 2017; Santos et al., 2020; van Leeuwen et al., 2019).

During the growing season, until around August, another important process is taking place, within the dormant buds, the differentiation of the primordial flowers and leaves, which will also be the base of the following year's clusters (potential fruitfulness). This event is also closely related to temperature. Khanduja & Balasubrahmanyam, (1972) show that plants have higher fruitfulness at temperatures between 20 and 30º C during this period on the previous year.

Sánchez & Dokoozlian, (2005) also show how after 32° C during the flower differentiation period, fruitfulness declines sharply, on the following year. This knowledge is very important to estimate the following year's yield and the agricultural practices to preserve it.

2.3.1 Effects of the rising Temperatures

Even under the best scenarios, an average temperature increases of 1.1º C is expected until the end of this century, which can aggravate to 2.5° C or even +3° C, depending on policies and human activities in general. This fact exposes us to a multitude of risks and, in particular for crops, to an increased risk of heat waves (IPCC, 2023), which may have consequences such as the ones presented on figure 1.

Figure 1: Example of a sunburn cluster damaged in an early phase of development.

A heat wave is defined as a prolonged period of abnormally high temperatures compared to what is expected. These have already caused a lot of damage in recent years in some of Europe's most important wine-growing areas, such as Alentejo in Portugal, during the summer of 2018. The main damage caused by these events is the dehydration of berries and leaves, which can ultimately lead to sunburn, caused by so-called thermal shocks. A thermal shock is defined by a net increase of 10-15° C that occurs in a short time, over a prolonged period, compared to the ambient temperature. These events expose plants to severe stress, causing the above-mentioned phenomena. VanderWeide et al. (2022) shows that the berries are indeed able to resist, but only if these occur sporadically. In fact, it has been studied that if two heat waves were to occur consecutively, the grape berries would not be able to repair the cuticular defence layer, leading to serious damage, including severe dehydration. It must also be said that the effects of a heat shock depend on the water, the type of soil and the speed and duration of the high temperatures (Wahid et al., 2007).

As explained in the previous subchapter (2.3), the entire phenological development of grapevines relies on a delicate thermal balance. It has been predicted that higher temperatures in late winter and early spring could create conditions for earlier budding, and this increases the likelihood that sub-polar continental winds from Siberia will reach the Mediterranean viticultural areas late freezing of shoots or young shoots (Sgubin et al., 2018). It is estimated that this could be around 40 days earlier by the end of the century. These winds bring with them markedly lower temperatures, often below 0° C, this leads to the formation of ice crystals within the young tissue of the plant, resulting in their death. The damage manifests itself through blackish necrosis and loss of turgor. These have the power to devastate high percentages of the year's crop, as most of the inflorescences, and therefore future clusters, are located in the early shoot internodes, and if these are destroyed, the plant does not have the capacity to regenerate new ones in the current year (Molitor et al., 2014; Poling, 2008). The literature, however, has conflicting opinions as forecasting models are based on many variables that are difficult to control and therefore highly prone to error (Sgubin et al., 2018). Due to this high variability between data, models predicting frost incidence trends do not always coincide.

Another effect of anticipated phenology, due to the hight temperatures, is also to adversely affect the number of inflorescence (Pagay & Collins, 2017). Indeed, flowering and fruit set are certainly two of the most delicate phenological phases. In fact, maximum daytime temperatures above 30-35° C during flowering can reduce fruit set by about 18%, although in some varieties the effects can be even worse, as in the case of pinot noir, which can be as much as 22-30%. This fact is also closely related to the ideal maximum temperature for pollen tube germination, which is around 28° C. With 35° C or more, this whole process is seriously challenged with direct effects on fruit set (Pagay & Collins, 2017).

It is recognized that photosynthesis has the optimal working temperature around 28-30ºC, but decreases a lot after 35° C (Martínez-Lüscher et al., 2015a). Other studies can certify that for prolonged periods of time with high temperatures, photosynthesis can decrease by 30-50%, also creating a delay in phenology, in fact in these cases plants are unable to keep the metabolism active, in order to carry on the maturation itself (Greer, 2013).

Finally, excessively high temperatures can promote heterogeneous ripening of the grapes (Greer, 2013). It is recognised that there are three different types of ripening: technological, which involves the accumulation of sugars; phenolic, which expresses the moment of ripening of the pips and skins, which involves the evolution and polymerisation of phenolic compounds, allowing them to be extracted, and the ripening of aromas. Ideally, the right time for harvesting is when these three types of ripening coincide. High temperatures therefore create a decoupling between the sugar content of the berry and the accumulation of anthocyanins. The faster rate of sugar accumulation can force the harvest, when aromas and phenolics are still immature, decreasing the overall quality and taste of the wine (Cook & Wolkovich, 2016; Palliotti et al., 2014a; Sadras & Moran, 2012a). Temperatures have a big impact also on the berry composition, but this topic will be explained in a subchapter 2.4.1.

2.4 Influence of water availability on grapevine growth

Grapevine is generally considered a water stress-resistant crop with a high degree of WUE (water use efficiency), which depends on the variety, the rootstock and the type of soil (Costa et al., 2016). Total water consumption of vineyards (100% crop evapotranspiration, ETc) under full water supply conditions (well-watered plants) varies from 300 to 700 mm per season depending on weather conditions (Medrano et al., 2015; Novara et al., 2018). The water usually comes from irrigation systems or precipitation. Water is crucial for ensuring plant nutrition and life, but also for maintaining turgidity in young tissues, which allows them to receive more sun to synthesise metabolites, and to assure the thermoregulation of the plants themselves in order to keep the temperatures as more in balance as possible (Grishin et al., 2021) . In the vine, this fact is even more important because the vine is a liana, and as such is subject to strong acrotony, which pushes the shoots higher and higher (Mullins et al., 1992).

Water is also essential to increase the availability of elements in the soil, allowing plants to absorb them into the xylem system in order to feed itself. Water from the xylem goes directly to the leaves, where it is excreted, allowing gas exchange and photosynthesis, which is fundamental to produce all the main compounds that plants need to ensure their survival (des Gachons et al., 2005a; Flexas et al., 1998). Thus, during vegetative growth, water availability is important to keep metabolism active, while water stress during flowering can delay shoot growth, decrease the number of fertile flowers, fruit set and thus yield (Mirás-Avalos & Araujo, 2021a).

During the initial phase of ripening, berries function as vegetative organs. Their water and nutrient supply come from the xylem, which originates from the roots. Therefore, the health of the berries directly relies on the availability of water in the soil. A green berry possesses stomata and chlorophyll, allowing it to perform photosynthesis and serve as a source of nutrients, much like a leaf. At this stage, the berry undergoes transpiration, leading to water loss (Kennedy, 2002). Throughout this phase, berries experience growth through cellular division. The greater the number of cells, the larger the size of each individual berry. Berry's size is closely tied to the number of seeds it contains. A higher seed count (up to a maximum of 4) results in increased hormone production and, consequently, larger berries. Hormones such as auxin and cytokinin, commonly known as growth hormones, regulate these processes. Thus, this phase represents a critical stage in the ripening process (Kennedy, 2002)

In the subsequent phases, water plays a pivotal role in maintaining an active metabolism and facilitating gas exchange and photosynthesis. Particularly in the final phase, maintaining an optimal balance of metabolites is essential for maximizing grape yield. While a high concentration of metabolites is desirable, it should not reach excessive levels. If the vine is subjected to severe water stress, it becomes incapable of providing water to the berries. As a consequence, the berries may cease their growth and subsequently become excessively dry. In extreme cases, this can result in the loss of the cluster and, consequently, a decrease in yield (Matthews & Anderson, 1989).

Water stress during these phases can significantly impact both the quality and yield of the grapes. In the initial phase, a lack of water can affect the metabolism and development of the berries, particularly regarding cell multiplication and the final count of berries, ultimately influencing their size. Additionally, the scarcity of water can lead to adverse phenomena like cavitations or embolisms in the trunk. Normally, water flows through the xylem in a chain-like manner, with each water molecule connected to those above and below it. When water is expelled from the leaves, it pushes the water in the trunk upward. However, the chain of water molecules can break, resulting in the formation of air bubbles within the xylem system and potential blockage of the vessels. Usually, this does not pose a significant issue as vines have a tendency to heal. However, if this condition persists for an extended period, the vine can experience vessel loss or, in extreme cases, the death of an entire section (Gerzon et al., 2015).

Lack of water can weaken the plant, impairing its ability to defend itself against fungal infections. Plants stressed by water shortage may have a weakened immune system and a decreased ability to respond to disease, making them more vulnerable to attack by pathogens such as powdery mildew.

2.4.1 Integrated effects of high temperatures and low precipitations, on grape quality

The effects on wine quality depend closely on the quality of the grapes themselves, and thus all agronomic aspects that can influence grape quality have a direct impact on the wine itself; climate change is one of the key players. The main compounds that determine the concept of quality are, for example, sugars, acids, phenols, and aromas, but also to the physiognomy of the grape itself, and in particular to the size of the berry (des Gachons et al., 2005a; Spayd et al., 2002a). From what has been expressed above, it can be understood that temperature and water quantity are two closely related factors, and in particular the effects that these two parameters have, under extreme conditions, on the cultivation of the vine, but especially on the ripening and consequently on the quality of the grapes themselves. The effects of extreme temperatures, rather than drought, can affect the quality of the grapes throughout the ripening period, causing a higher production of sugars, which will lead to too much alcohol production, which can lead to problems during fermentation, causing it to slow down or stop. Moreover it brings to too high a loss of acids, in fact in these conditions the respiration of malic acid continues overnight, leading to an imbalance the amount of alcohol and acids that is fundamental for a maintain a taste balance of the wine itself (Ryu et al., 2020; Santos et al., 2020). As already mentioned, this is true as long as the temperature allows photosynthesis to occur, otherwise there will be a complete halt in ripening, which as a result will lead, in the best-case scenario, to a delay in the harvest, or to scalding of the berries and leaves with consequent damage to production and the plants themselves (D. Greer, 2013). In addition to this, high temperatures also lead to problems with the synthesis, methylation and accumulation of polyphenols and anthocyanins. There is evidence that too high day and night temperatures, first at veraison, can decrease these three factors, resulting in lower anthocyanin and phenolics. In addition, other studies show that aroma production can also be affected in the same way, leading o difficulties in their synthesis and accumulation (Asproudi et al., 2016; Gaiotti et al., 2018; Rogiers & Clarke, 2013), moreover the aromas can vary, going towards flavours such as over-ripened, cooked or red fruit jam (D. Greer, 2013). All of these mechanisms usually starting above 35° also because at those temperatures, the real temperature on the clusters surface is above the environmental temperature of 12 or even more degrees (Bernardo et al., 2018).

Speaking of water stress, the worst effects of lack of water occur between the vegetative growth period and the veraison, during which the berry is undergoing cell multiplication, so a period of drought will reduce the final size of the berry permanently; this fact can have both positive and negative effects, if the berry is not too small, it could be considered as a positive fact due to the increase in the pulp/peel ratio, which increases the concentration of metabolites and thus the quality. It has also been shown that a period of water stress, which is not severe, can have important positive effects on metabolism by increasing the synthesis of polyphenols, such as anthocyanins, and other secondary metabolites such as aromatics (Rogiers & Clarke, 2013; Santesteban et al., 2011; WANG et al., 2003).

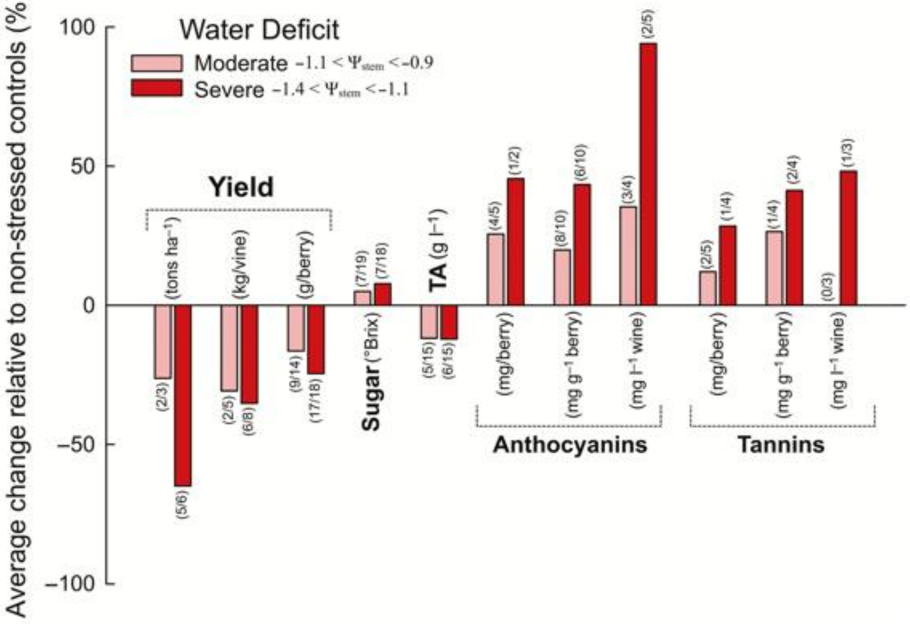

Figure 2: Representation of the effect of water stress, split between moderate and severe (Wang et al., 2021)

It also accumulates some solutes to keep the water potential as low as possible, in which case the plant achieves maximum water use efficiency, also changing the anatomy of the water vessel. This reduces photosynthesis, and thus vegetative growth, of shoots, leaves and tendrils. This remains accurate when discussing about moderate water stress, but the situation shifts significantly under severe water stress; in this case, the plant tends not to perform transpiration, closing its stomata. The literature shows that for a decrease in water potential, in severe conditions, of 0.2 MPa there is consequently a 10 percent loss of yield, and that an extreme water deficit with a stem water potential, less than -2 MPa generally leads to complete loss of yield and leaf canopy, with little chance of recovery (G. A. Gambetta et al., 2020). If the plant does not reach this point, the effects are like those of moderate water deficit, with an increase in sugars, a loss of acidity, a high increase in polyphenols (specifically to reduce the number of free electrons resulting from the condition of severe physiological stress, with the aim of producing ROS) and an increase in volatile compounds. These reactions are also closely related to variety and rootstock, so even the results in the literature do not always agree what individual effects are due to water stress on a case-by-case basis. (Chapman et al., 2005; Griesser et al., 2015; Martínez-Lüscher et al., 2015a; Wang et al., 2021). Obviously, the consequences of the conjunction of both factors, temperature and precipitation, sharpen the overall picture even more, exacerbating the consequences (Santos et al., 2020).

2.5 Influence of radiation on grapevine growing and grape maturation

Solar radiation plays a fundamental role in the growth and life of plants. It is well known that solar radiation consists of important particles named photons, which are the main reason for plant life in our world. This radiation is dispersed in many wavelengths, so it’s possible to distinguish different types, such as infrared at more than 700 nm, the visible wavelength between 700 and 400 nm and UV radiation, which is divided into three main groups: UVA from 400 to 315 nm, UVB from 315 to 280 and UVC below 280 nm. The last two are the most important because of the impact they can have, if they reach the surface, on living beings, causing much damage. Fortunately, UVC is completely absorbed by the ozone layer in the stratosphere and UVB almost completely, in fact only 5% of this type of rays reach the earth's surface. The current level of UVB concentration exists due to the Montreal Treaty, a rule stating that harmful chemicals like ODS shouldn't be used. This is crucial to safeguard the ozone layer and, consequently, life on Earth (Bernhard et al., 2023; Heijde & Ulm, 2012).

Under normal conditions, UVB plays an important role for plants; studies like (Heijde & Ulm, 2012) show that each plant is equipped with photoreceptors that enable it to accurately perceive solar radiation so that it can optimise its response to various and specific environmental and climatic conditions. UVB is an important regulator of plant morphology, using radiation (light saturation?) as an environmental indicator to regulate their metabolism and growth.

Other studies show that plants inherently have various ways of responding to high concentrations of UVB such as: DNA repair, arrest of protein synthesis, production of important natural defences such as ROS, flavonoids and anthocyanins, which accumulate in their most sensitive spots such as leaves, pollen, fruits and flowers (Bernardo et al., 2018), and also through the reduction of stomatal aperture, reduction of leaf size and photosynthesis. Other studies show a correlation between UVB and drought responses (Barnes et al., 2023; Jansen & Bornman, 2012). Barnes et al. (2023) also show how UVB exposure can have positive effects in the implementation of natural defence against fungi and diseases, including by stimulating ROS and phenol synthesis. They also show how this exposure can improve the colour, taste, quality, and nutraceutical values of food.

Certain studies predict a decrease in UVB radiation, as a result of ozone layer replenishment, of about 2-5% in the north and 4-6% in the south, with some exceptions related mainly to the more massive population centres, the perspectives on this front are quite optimistic (Bernhard et al., 2023).

In addition to the UV also the Photosynthetically Active Radiation (PAR), is very important for the plant growing, it refers to the portion of the light spectrum that is available for plants to conduct photosynthesis. This radiation is approximately between 400 and 700 nanometres (nm) and corresponds to visible light (Oyarzun et al., 2007). Plants use PAR to convert light energy into chemical energy through photosynthesis, a process essential to produce sugars and biomass. Thus, an adequate amount of PAR is critical for plant health and development. Vines are plants that require a significant amount of PAR for effective photosynthesis. During the vegetative growth phase, vines typically require a PAR light flux density of 800 μmol/m²/s, during the day, for effective photosynthesis (Cartechini & Palliotti, 1995). During this phase, plants seek to develop healthy, strong leaves to accumulate energy reserves for future fruit production. On the other hand, during the flowering and fruiting phases, the need for PAR may increase. At this stage, the vine needs even more PAR to support flower formation and cluster development. The amount of PAR required can vary, but usually a PAR light flux density around 900 μmol/m²/s, is considered adequate for effective photosynthesis during this critical phase. However, the exact amount of PAR required depends on several factors, such as the growth stage of the vine, the specific variety and the environmental conditions (Smart & Sinclair, 1976a), and this could be a problem in an agrivoltaic system, not least in order not to increase the negative effects of too much shading. If this were to happen, the vine would not have enough energy from carbon assimilation to keep photosynthesis and thus metabolite production active. Cartechini & Palliotti, (1995) show that there are many other factors directly related to PAR such as leaf chlorophyll content, vigour, yield, quality, through the production of sugars, polyphenols and aromas. Conversely, vine plants also have a limit in the utilisation of solar radiation, beyond which they will not be able to increase their photosynthesis ratio, leading to an increase in temperature, which brings photosynthesis itself to a standstill, exceeding a temperature around 35°. If this should also occur under conditions of water stress, the vine leaves, in addition to temporary photoinhibition, could show phenomena of chlorosis and necrosis, thus leading to low intrinsic water utilisation efficiency and excessive exposure of the clusters to sunburn (Santos et al., 2020).

2.6 Influence of air CO_2 concentration on grape vine growth

It is generally acknowledged that CO_2 is one of the main greenhouse gases causing global warming, but it is also the main element that plants need for the organisation of carbon, which is one of the most important processes to ensure photosynthesis and thus plant life. CO_2 is used in photosynthesis to produce sugars, as in the following reaction: $6CO_2 + 6H_2O \rightarrow$ C6H12O6. This reaction also requires the energy of photons striking chlorophylls, which initiate the electronic cascade to promote the formation of ATP and NADPH, which is fundamental to this and almost all reactions in biology. This is a reduction reaction, which takes place in the stroma of the chloroplast. The formation of triose-phosphate takes place in the Calvin cycle, using the ATP and NADPH formed during the light phase. This process is, however, specific to C3 plants, which differ from C4 plants; In the first case, RuBisCO, which is the most important enzyme in this process, initiating the reactions of the Calvin cycle, is localised in the cells of the mesophyll, which are in direct contact with the stomatal cavity, and therefore with the atmospheric air, as opposed to the C4 plant where RuBisCO is localised in the cells of the sheath where it is much more concentrated, so it is possible that this type of plant does not benefit too much from the increase in CO_2 (Cure & Acock, 1986).

2.6.1 CO_2 in the climate change

Nowadays, the amount of CO_2 is the highest it has been in 26 million years, until the pre-industrial level, about 150 years ago, the global average of the amount of CO_2 in the air was about 260 ppm, then it steadily increased, and now it is about 400 ppm, but it is expected to increase, at least, to 700 ppm before the end of the century. (Bindi et al., 2001; Gonçalves et al., 2009) show how more CO_2-enriched air can have several positive effects on vines, in particular they show an increase in photosynthesis, and consequently in growth and yield of around 45%. It must be said that these studies do not relate increased CO_2 to increased temperatures and lack of water, but it is interesting to note how (Cure & Acock, 1986) underline that the positive effects of having a greater quantity of CO_2 they are more pronounced when crops are stressed, and vice versa. It has also been pointed out in other crops that, following an increase in CO_2 concentration, plants significantly increase their ITE (instantaneous transpiration efficiency), of water by around 68% for C3, while also reducing stomatal conductance by a good 20%, as a result of which they will do less photosynthesis and use much less water to achieve the same metabolic effects. For this reason, there is conflicting opinion in the literature on the impact that higher levels of CO2 in the air can have on plant development, which is occurring now and will increase again in the coming years (Long et al., 2004; M. J. Paul & Pellny, 2003).

2.7 Microclimate of the vine and relative humidity

Microclimate, unlike the general climate or macroclimate that describes a large geographical area, refers to more localised conditions that can vary even within a relatively small area, such as a vineyard or canopy. The canopy microclimate plays a crucial role in vine cultivation as it has specific conditions that differ from those outside (Schultz, 1995). The effects of the microclimate are influenced by several environmental factors previously discussed, such as temperature and windiness, but also by structural factors related to shape, type of training system and variety. For example, a wider canopy with a larger leaf area increases shading and humidity, reducing temperatures. However, this can lead to higher water consumption and a higher risk of diseases such as Botrytis (Haselgrove et al., 2000; Smart, 1985a). On the other hand, a smaller canopy with a concentrated leaf area has the opposite effect. It reduces shading and humidity and increases the temperature of the cluster due to the increased exposure to sunlight. Under normal conditions, this increased exposure promotes cluster ripening and the production of important compounds such as polyphenols and aromatic precursors. However, increased exposure of the bunch also poses a risk to its integrity. In the context of climate change, higher temperatures and less water availability will increase the risk of bunch scorch if the cropping system exposes more bunch surface area, as is the case with a narrow canopy. Conversely, a large canopy may better protect the cluster from sunburn but will require more water to support the metabolism of the plant. The higher humidity within the canopy may favour the development of fungi such as botrytis or powdery mildew, damaging the clusters. all this leads us to the conclusion that changes and adaptations in cultivation practices will be necessary in order to optimise production and plant health. In this context, the application of agrivoltaic could offer several advantages (Ferrara et al., 2023; Haselgrove et al., 2000; Matese et al., 2014; Schultz, 1995; Smart, 1985).

2.8 General solution to mitigate the climate change

As explained thus far, it is crucial to confront the effects of climate change on grapevines effectively to minimize damage over the years. Two main approaches can be identified: long-term and short-term.

Regarding long-term solutions, existing literature strongly supports the idea of shifting grapevine cultivation to adapt to climate change. This transformation will see viticulture gradually moving to higher altitudes and more northerly regions, including countries like Germany, Denmark, and England in Europe, mirroring global trends. This geographical shift needs careful consideration of adjustments to clones and rootstocks, guided by a thorough analysis of local terroirs. This optimization is vital to align grapevine performance with evolving weather patterns. Emphasizing the breeding and selection of new clones and rootstocks to bolster resistance against extreme weather conditions and diseases is of utmost importance, particularly for the preservation of viticulture in southern Europe (Fraga et al., 2012; Santos et al., 2020; van Leeuwen et al., 2019).

In terms of short-term solutions, there are several crucial aspects to consider. Firstly, the implementation of efficient irrigation systems wherever possible is highly recommended to counter the sharp reduction in rainfall. Additionally, modifying agricultural practices, especially grapevine management, to delay cluster maturation, reduce microclimate temperatures, and optimize Water Use Efficiency (WUE) are paramount considerations (Salazar-Parra et al., 2012; Santos et al., 2020). Actions like late pruning or increasing trunk height can contribute to these goals. Soil management is equally vital due to high erosion and loss of fertility in the today’s fields. Reducing soil tillage, whenever possible, and integrating cover crops can be effective strategies to combat these issues. Moreover, employing shading covers, reflective products, or particular rocks can prove to be valuable tools for farmers. In fact the use of white or green nets has shown to significantly reduce temperatures, especially when allowing good air circulation to prevent an increase in relative humidity (Fraga et al., 2012; Santos et al., 2020; Tomasi et al., 2011; van Leeuwen et al., 2019). Furthermore, research has explored how products like kaolin enhance light reflectance, WUE (Water Use Efficiency) with a notable increase of 18% compared to unsprayed vines and reduce plant evapotranspiration and temperature by approximately 1.3°C under extreme climatic conditions. Additionally, it contributes to increased evapotranspiration during warmer hours and anthocyanin retention (Brillante et al., 2016; Brito et al., 2019; Dinis et al., 2016; Frioni et al., 2019; Lobos et al., 2015).

Furthermore, advancing knowledge and utilizing precision viticulture tools in the vineyard can offer an optimal approach for constant monitoring of plant conditions, facilitating a deeper understanding of their physiological requirements. Emerging technologies like robots, drones, probes, remote sensing, drip irrigation, geo-referencing of plants and vineyards. The integration of solar panels could also prove highly beneficial in the near future, aiding in addressing the challenges posed by climate change. As previously mentioned in chapter 2.2, agrivoltaic systems presents a significant solution to mitigate the issues brought about by climate change. Specifically, they can bring numerous advantages to vine cultivation. However, there is still a scarcity of publications on this subject due to its status as an emerging technology like robots, drones, probes, remote sensing, drip irrigation, geo-referencing of plants and vineyards. The integration of solar panels could also prove highly beneficial in the near future, aiding in addressing the challenges posed by climate change. As previously mentioned in chapter 2.2, agrivoltaic systems presents a significant solution to mitigate the issues brought about by climate change. Specifically, they can bring numerous advantages to vine cultivation. However, there is still a scarcity of publications on this subject due to its status as an emerging technology (Barron-Gafford et al., 2019; Bwambale et al., 2022; Ferrara et al., 2023a; Kansara et al., s.d.; Nikolidakis et al., 2015; Santos et al., 2020; Shafi et al., 2019).

2.9 Agrivoltaic

2.9.1 Agrivoltaic in other crops

In general, it is well established that the agrivoltaic systems can help to lower the temperatures of crops and the soil, increase the WUE, but also increase the energy production performance of the companies. Barron-Gafford et al., (2019) show how in an agrivoltaic system, in crops such as tomato, jalapeño, and chili peppers, there can be important effects. The study points out how temperature decreases, particularly due to the reduction of radiation, due to shading from solar panels, which in fact drops from 1200 μmol/m²/s, on average, to 500-600 μmol/m²/s. Certainly, this is also caused by the type and shape of the agrivoltaic system, how close each panel is to each other, and what their inclination is. In Barron-Gafford et al. (2019), authors used one meter between each row of panels, which had a 32° of inclination and were placed at a height of 3 meters. The decrease in radiation under the panels resulted in a decrease in temperature of 1.2° C during the day but increased it by 0.5 +- 0.4 º C during the night. the cover also increases the water use efficiency up to 157% for jalapeno. Barron-Gafford et al., (2019) also show an increase in yield, from 0 to 3 times the average for bell pepper. This shows that in this case there can be great positive effects, but these can be distinct depending on the crop. In fact these facts are partially confirmed by the study of Juillion et al., (2022) in which they show that in an apple orchard with a dynamic agrivoltaic system, capable of modifying shading between 5 and 85 percent, with an average shading rate of 50-55 percent, the effects, even in this case, were important. First, the temperature dropped by about 3.8° C in the shaded area, with a 14% increase in relative humidity, also allowing better avoidance of late frost damage, with a higher percentage of fruit trees under PV panels (+31%) and number of fruits per fruit tree (+44%) in 2021. The panels also created a less stressful environment that reduces production fluctuations that apple trees tend to suffer greatly. Irrigation was also reduced in a range of 6 to 31 percent, but yield in general were also reduced, not allowing the standards for this type of crop of 40 t/ha to be maintained. These data highlight the difference between crops, particularly between fruit trees and horticultural crops. For these reasons the decrease in PAR could also be a problem for grape cultivation.

2.9.2 Effects of agrivoltaic systems on viticulture

As mentioned earlier, grapevines need about 800-1000 μmol/m²/s, on average, depending on the growth stage, to have optimal photosynthesis rates, thus the presence of panels can be a limitation. Studies such as Ferrara et al., (2023) show that there are many effects related to decreased PAR in vines. They show that over the 3 years of research, there was an overall decrease in evapotranspiration for the vines, although this increased at midday, where the plants under the panels were able to do more photosynthesis than the control. There was a decrease in stomatal density in the shaded leaf sublayer, with a 27% increase, however, in the exposed one, and a 23% increase in leaf area for the plants under the panels. These mechanisms are due to the particular environment present under the solar panels, and result from the plants' reaction to the shading itself. As expected, water consumption and water potential were also less negative than in the control.

In the same study, Ferrara et al., (2023) presents the effects on yield and quality. Yield decreases in a not significant way, also due to the decrease in PAR, but acidity increases, in all aspects, which is definitely a very positive aspect, especially for white and sparkling wines. For reds, results show a decrease in the amount of polyphenols, in their research conditions, due to too low irradiation, although they had this big gap between the values only in the first year, then the loss of polyphenols was about 15-20% compared to the control. This highlights that perhaps this technology is not optimal for red wines that are supposed to have a long aging period, but surely it also depends, as mentioned above, on the properties and shape of the agrivoltaic system, and in this case the distance between each row of panels is very important. Although this is exhaustive work, there are other voices outside the chorus, such as Ahn et al. (2022), in which its shown that grapes are not greatly affected by shading, at least not so much as to have significant consequences on growth and ripening periods. Ahn et al., (2022) show how there were no statistical differences in the amount of chlorophyll, dry mass, sugars, acidity, and even regarding the figure for the amount of anthocyanins. These results are also partially confirmed by Grison et al. (2022). It is also important to point out that in this (Ferrara et al., 2023) work the energy gained from the panels compensates for the loss of yield for the winery, and this is also confirmed by the work of Malu et al., (2017) in India, where it is estimated that the yield of the panels can, under optimal conditions, be more than 10 times that of the grapes. It should also be kept in mind that this is preliminary work and that all the specifications and techniques have yet to be discovered and refined. In fact, it is not yet clear how varying conditions, such as variety and type of panels, change the results obtained, as indeed confirmed by the conflicting studies highlighted above.

3 Material and methods

3.1 Plant material and growth conditions

The experiment was carried out in two fully grown experimental vineyards in the Lisbon winegrowing region, Portugal (Figure 3). Data were collected at Instituto Superior de Agronomia (ISA) vineyard, located at Tapada da Ajuda (38°42'24.61" N 9°11’05.53" W).

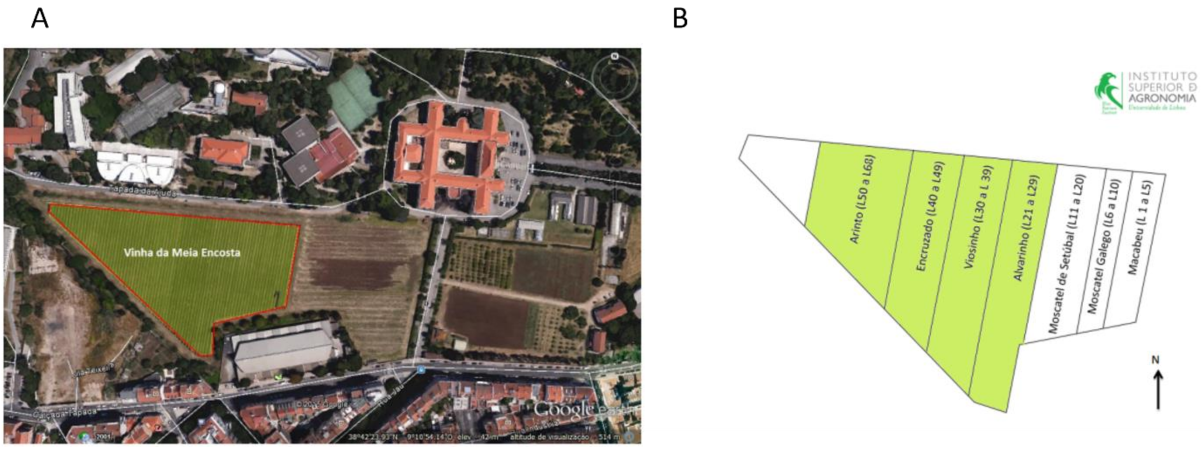

Figure 3 Top view of the Tapada de Ajuda and the ISA university department. Aprox scale of 1:4250. *B: Scheme of the grape varieties planted in the Vineyard of Meia Encosta. Pointed variety in study (Victorino et al., 2017).*

The climate is classified as Mediterranean type with an Atlantic influence (cas/csb) (Köppen, 1936). This vineyard consists of spur pruned vines trained on a vertical shoot positioning trellis system with two pairs of movable wires. One portuguese white variety was selected for this study: Viosinho. The 'Viosinho' white variety was grafted onto 1103 Paulsen rootstock, planted in 2006 and spaced 1.0 m within and 2.5 m between north–south oriented rows. Water is supplied with a drip irrigation system, and irrigation is managed using a soil moisture sensor. Readily available water was maintained over the whole growth cycle and reduced to moderate water stress at veraison until harvest. Shoot thinning was taken out to reduce the shoots variability. Soil analysis was made in order to understand the soil composition regarding the texture, the organic matter content, the electrical conductivity, the macronutrients and micronutrients levels of the soil. These results are presented in chapter 4.5.

The 2023 season, depicted in Figure 4, featured a dry spring, with an average monthly precipitation of 15 mm from March to June. However, June saw a notable deviation with a maximum rainfall of 20 mm, a departure from the dry trend experienced since winter. Additionally, the year was marked by a warm and dry summer, recording zero precipitation in July and August and maintaining an average temperature of 20°C from June to September. The observed values for this year closely parallel those recorded over the preceding 30 years. Specifically, the average normal temperature in winter was approximately 12ºC, while during the summer months, it remained around 21ºC. Similarly, precipitation patterns demonstrated consistency, with an average normal precipitation of roughly 93 mm in winter and approximately 39 mm in summer over the 30-year period. (IPMA 2023).

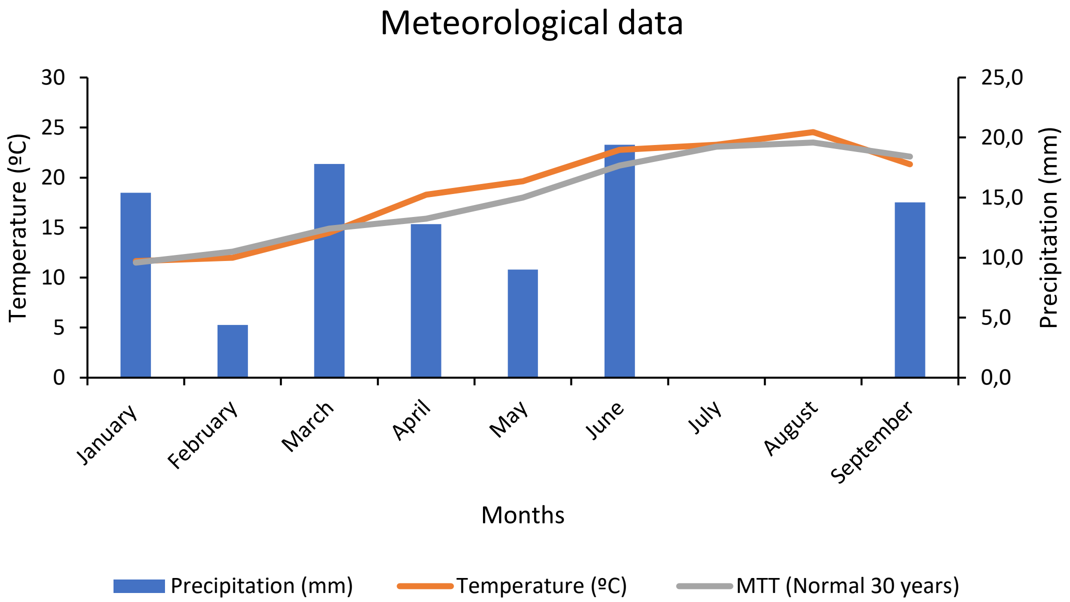

Figure 4: Meteorological data collected from the weather station, placed in the Viosinho vineyard, during the year 2023. *Precipitation (mm) and Temperature (°C) values during the 2023 season, from January until September. Normal values (MTT) obtained in IPMA (IPMA, 2023).*

3.2 Experimental design

The experimental setup involves two main plots: the PV plot and the control plot. Standard management practices were applied consistently across both plots. The need for plot separation arises from the plan to establish an agrivoltaic park within the vineyard. Due to the substantial size of this structure, randomly distributing control grapevines throughout the vineyard was not feasible. Therefore, it became important to physically segregate the two plots. Given the inherent spatial variability, this separation was crucial for a meaningful comparison of the plots.

Achieving optimal results necessitated the careful selection of strategic points within the plots that exhibited minimal differences between the two treatments. This was essential for a thorough evaluation of the prospective impact of solar panels on both the plants and the wine produced.

The initial step in identifying these key points involved creating georeferenced kriging maps for Viosinho vegetative data, encompassing parameters like pruning weight, trunk diameter, the number of spurs per plant, and phenological development (detailed in Chapter 4.1). To accomplish this, we utilized QGIS® software (version 3.28), with the settings of the plug-in Smartmap (Pereira et al., 2022), known for its capability to analyze and integrate datasets, presenting them spatially on a map. This approach provided an approximate assessment of vegetative development in the field, aiding in the judicious selection of optimal vineyard areas.

It's noteworthy that prior studies by Victorino et al. (2017) have already established the presence of spatial variability in the Viosinho vineyard, both concluding its absence. Furthermore, Machado (2018) research highlighted significant differences in soil composition, affirming how our thorough approach in assessing spatial variability to pinpoint the most suitable vines for our study is highly relevant.

Regarding the Kriging map, strategic points were selected with 5 plants each to ensure similar performance between the PV plot and the control plot, facilitating a fair comparison. Four smart points were designated for the PV plot and five for the control plot due to its higher variability, as depicted in Figure 5.

Initially, the installation of the agri-voltaic system was planned before summer to commence the full experiment. However, logistical issues led to postponement, prompting a shift in the thesis objective. Consequently, the decision was made to evaluate the spatial variability within the study plot to discern potential vegetative, physiological, phenological, and qualitative differences between the two plots in the vineyard.

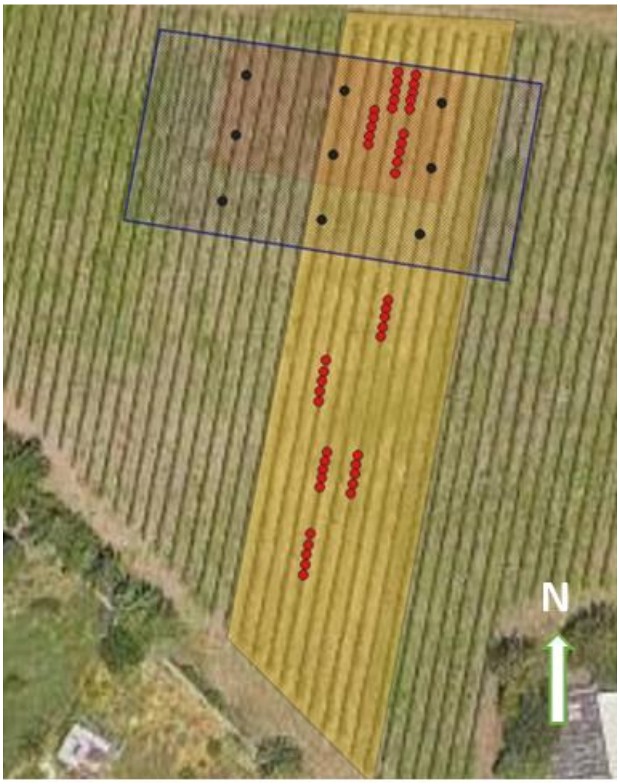

Figure 5 The figure represents the aerial image of the Viosinho vineyard. The red dots represent each plant in the selected Smart point.

3.3 Data Collection

Soil analysis

To assess the nutritional condition of the vineyard soil, analyses were performed during March. The sampling was done covering three specific rows: 32, 35, and 38. Within each row, three samples were collected from the middle and three from under the vines. For each sample area, three samples were collected using a soil sampler probe at approximately 20 cm deep.

Leaf petiole analysis

To assess plant nutrition, petiole analysis was conducted. This analysis was conducted at the end of April, specifically during the Flowering stage, to allow for any necessary corrections in plant nutrition before the ripening stage. Fifty petioles were collected from two smart points per plot. Petioles were carefully taken from the opposite side of the bunches and placed on dry absorbent paper in order to be taken to the laboratory.

Phenology

To determine the general growth the phenology was observed weekly using the BBCH scale (LORENZ et al., 1995). Three photos were taken at every smart point, one showing the row, one showing entire smart point canopy of the smart point itself, and the last one showing the reproductive organs evolution, such as buds, flowers, and berries.

Figure 6 Two picture of the same row of the Viosinho vineyard. Picture A was taken during the budburst in the first week of April. The picture B was taken during June, representing the vegetative evolution through the year.

Vegetative parameters

Several vegetative parameters were evaluated, such as shoot growth, leaf area, expose leaf area, and the canopy porosity. To evaluate shoot growth measurements of shoot length were taken weekly from the same two shoots on two selected plants within each smart points. In total, 36 shoots were measured in the Viosinho plots, with 16 from PV and 20 from the control.

Measurements started from the shoot's base and extended to the last fully grown leaf. A leaf was considered sufficiently grown if the lateral nerves were at least 3 cm long. The vigour of the grapevine was evaluated by calculating the leaf area using the methodology described in Lopes & Pinto (2005).

The leaf area was estimated by counting the number of leaves and measuring the length of the two mains lateral veins on the largest and smallest leaves. It's essential to highlight that this approach is non-invasive and revolves around determining the average leaf area of the chosen shoots (Lopes & Pinto, 2005). These measurements were obtained from two shoots of two plants at each specified smart point in both plot groups during significant phenological stages: flowering (BBCH 61 - 26/04), pea size (BCCH 73 - 16/05), veraison (BBCH 83 - 22/06), and maturation (BBCH 85 - 3/07).

The exposed leaf area was analysed on all the plants per SP for each plot at specific phenological stages, flowering (BBCH 61 - 26/04), pea size (BCCH 73 - 16/05), veraison (BBCH 83 - 22/06) and maturation (BBCH 85 - 3/07) respectively. The exposed leaf area was calculated as the product of the average height and average thickness of the canopy (without accounting for any potential canopy porosity).

Finally, in order to estimate the porosity of the canopy, image analysis was performed on RGB images taken parallel to the canopy. Canopy holes were segmented in the image using colour threshold, similar to what was performed in (Victorino et al., 2022). At each smart point, for each plant, one RGB image was captured using a commercial camera (Nikon D5200) equipped with a Sigma 50 mm F2.8 macro lens (Sigma corp., Kanagawa, Japan) in auto-mode. The camera was securely mounted on a tripod, positioned approximately 2 meters away from the row axis and 1 meter above the ground (see Figure 7). A blue background was placed behind each imaged canopy segment, and a fixed plastic bar was positioned beneath the canopy along all the smart points to serve as a reference scale. Images were taken at two phenological stages: pea size (BBCH 73) and maturation (BBCH 85). Each image represented a canopy segment of approximately 1 meter (equivalent to about 1 vine, as shown in Figure 7, and was individually analysed for all the plants at each smart point in both plot groups.

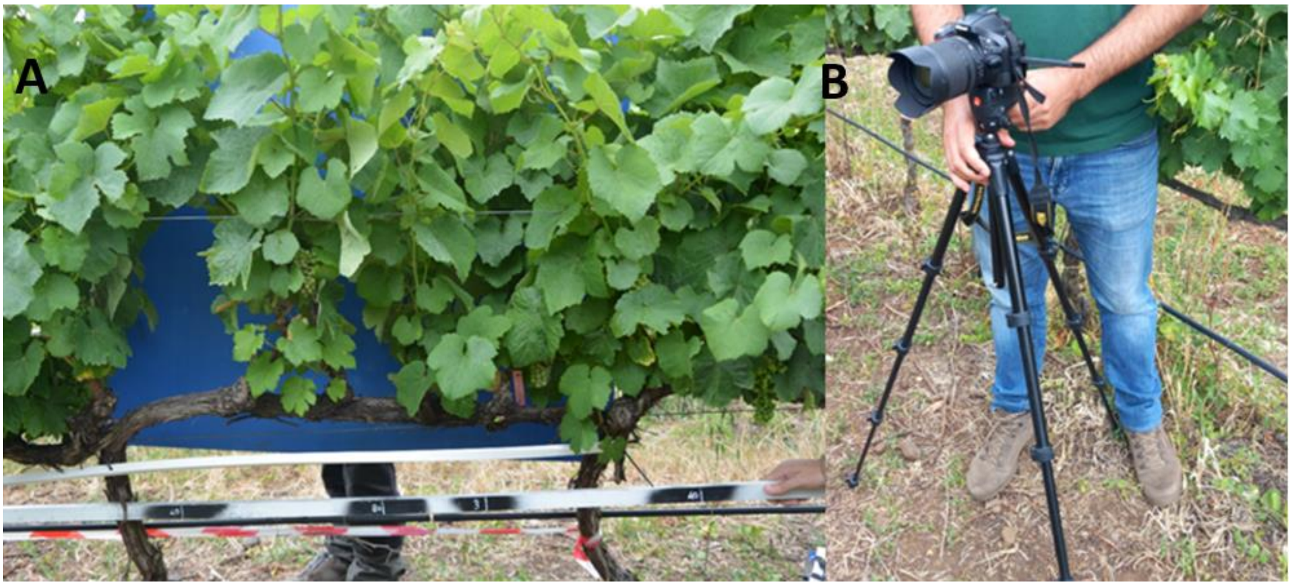

Figure 7 Example of the RGB image collection set up. Figure A represent the canopy with a blue background and a meter to measure the distance. Figure B represents the Nikon camera used, with the tripod used to stabilized it.

Canopy and Soil temperature

To determine the canopy and soil temperature, thermography measurements were carried out at specific phenological stages: Pea size (BBCH 73 - May 16), veraison (BBCH 83 - June 22), and maturation (BBCH 85 - July 3). Thermal images were captured using a FLIR A35sc camera (Teledyne FLIR®, Wilsonville, OR, USA), targeting both the canopy and the row as shown on figure 8. At the end of each smart point, an aluminium bar was placed to serve as a reference point. The camera was strategically positioned at a diagonal angle to ensure visibility of the aluminium bar (Figure 8). Images were collected the day before irrigation when plant water stress was highest doing one shot per smart point.

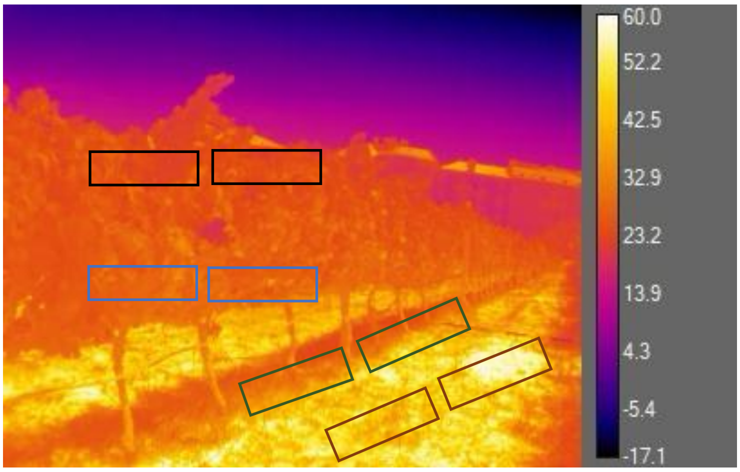

Figure 8 Example of a thermographic image collected from one smart point of Viosinho, with colour scale. The image was collected form the western part of the canopy, approximatively at 16:00 in the afternoon. *Two squares in black represent the upper canopy, the blue squares the lower canopy, the green squares were selected in the row and the orange squares represent the inter row.*

Stem water potential

To evaluate the vine's water status, a Scholander pressure camera was used as showed in the figure 9. The assessment focused on the stem water potential (SWP) at crucial phenological stages, starting with flowering (BBCH 61 - April 26), pea size (BBCH 73 - May 16), and maturation (BBCH 85 - July 3). This evaluation involved examining two leaves of two different plants from each smart point in both plots.

Measuring stem water potential (SWP) entailed enclosing a leaf in a plastic bag surrounded by aluminium foil for 45-120 minutes. This process temporarily stopped leaf transpiration, allowing it to reach a water potential equilibrium with the stem. Using the pressure chamber, data was collected, and measurements were conducted in the early afternoon on sunny days to ensure the most accurate samples, following the prescribed methodology by Greenspan et al. (1996). Analysis was performed the day before irrigation when plant water stress was highest.

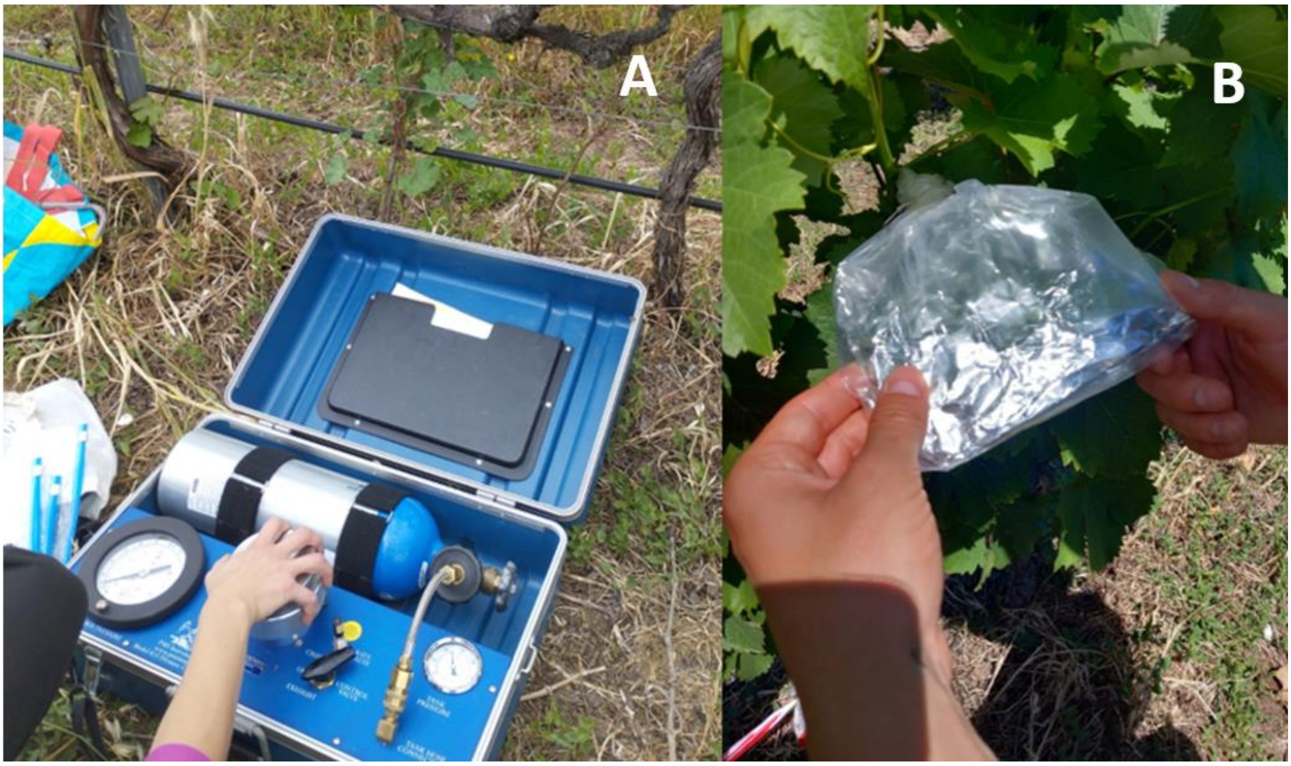

Figure 9: A Top view of the Scholander pressure chamber, with the gas bottle. B represents the aluminium sheet and the plastic bag, used to cover the leaves.

Leaf gas exchanges

Leaf gas exchanges measurements were made during the pea size (BBCH 73 - 16/05), veraison (BBCH 83 - 22/06) and maturation (BBCH 85 - 3/07). Firstly, the CIRAS-3 Portable Photosynthesis System was used after the pea size the Li-6400 Portable Photosynthesis System (Li-Cor, Inc. Lincoln, NE, USA) was used, because some technical problems of the first one and for the ease of use. The data was taken in the early afternoon, in full sun days between 13:00 – 16:00 h, to have the best representative samples, based on Toro et al. (2019). It has been analysed one adult leaf of each plant for every smart point. The leaves were selected visually in the mid- upper part of the canopy. The parameters analysed were, respectively, the photosynthesis rate and the stomatal conductance.

Figure 10 Illustration of the IRGA Li-6400 used for the data collection, with the tripod to fix the camera for the evaluations.

Yield and yield components

Near the harvest, a detailed analysis of the bunch characteristics was conducted. Bunches were collected at BBCH 85-89, specifically on the 25th of July. A total of 45 bunches were sampled, one from each plant.

In the laboratory, bunch weight was measured using a table scale (KERN FCB v1.4). Additionally, a picture of each bunch was performed, as shown in picture 11A, using a standard commercial camera (Nikon D5200) against a blue background. These images were utilized to estimate the bunch's projected area using a custom-made Python script based on colour thresholding.

Following this, all the berries were removed from the bunches to measure the rachis length, number of rachis ramifications, and the number of berries. Subsequently, the berries were carefully arranged on a table for image collection (Fig. 11B) using the same camera. A custom-made Python script was employed for berry counting.

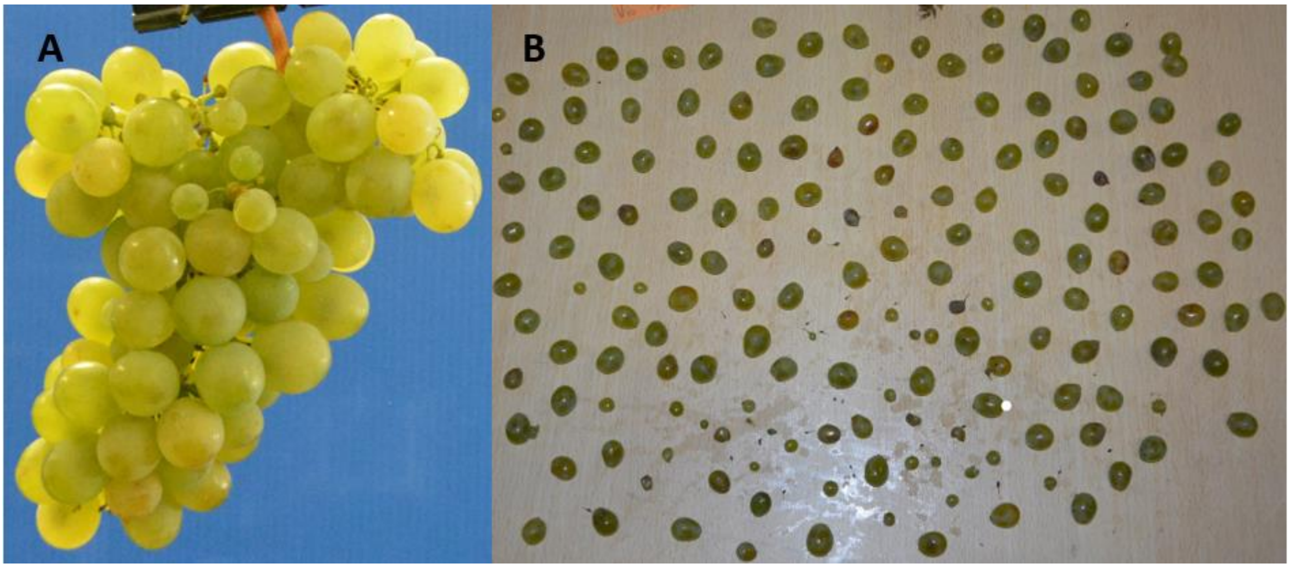

Figure 11: A Bunch image with a blue background. B: Image of berries displayed on a table and with the rachis beside.

With the aim of do the maturation control, following veraison (BBCH 83 - June 22), a systematic sampling regimen was established. Every Monday, 100 berries were carefully selected for analysis, taken from some plants within the smart point and other from contiguous vines, to reduce the amount of destroyed sampling, to be later analysed in the laboratory (Figure 12). These samples underwent standard maturation analysis, including measurements of weight, must volume, sugar content (Brix), potential alcohol content, pH level, and total acidity. All of these analyses were conducted in accordance with the standardized OIV measurement protocols (Curvelo-Garcia. 1988) until the harvest.

Figure 12: Image of the laboratory procedure analysis, particularly the solution of must and reagents in order to analyse the total acidity. In the pictures are presented the Viosinho samples, divided in PV and control along with other varieties s which were being analysed at that time.

All the plants were harvested on the 1st of August, and a comprehensive assessment was conducted, which included counting the number of bunches per plant and measuring their total weight. Simultaneously, the harvested bunches underwent a visual analysis for disease infection. This analysis was separated in two parameters: the intensity of the disease infection, which stands for the number of bunches visually affected and the severity of the infection which stands for the percentage of berries affected on average in each bunch. The level of infection was expressed as a percentage based on visual observation. Additionally, a visual analysis was performed to determine the extent of bird damage. To simplify this measurement, it was decided to take in consideration only bunches that were significantly damaged, with more than 50% of the berries eaten, based on visual observation, as it was not possible to evaluate the exact number of eaten grapes.

Oenological parameters

The wine was done doing a micro vinification the same day of the Harvest. The grapes, as soon as they arrived in the cellar, were destemmed in a destemmer (Fig. 13A). Firstly, the PV grapes, then the control ones. After this first phase, the grapes were pressed by a manual wine press, figure 13B. Finally, the must was moved in a glass jar figure 13 C/D, in order to do the alcoholic fermentation.

Figure 13 (A) destemmer in function with Viosinho grapes. (B) manual wine presser, with destemmed Viosinho grapes. (C and D) Viosinho must, waiting for the alcoholic fermentation in glass jars.

Following the vinification, a 100 ml sample of grape must was collected for laboratory analysis to determine the final must parameters. The laboratory analysis encompassed measurements of sugar content (Brix), potential alcohol content, pH level, and total acidity, in accordance with the OIV standard methodology.

Subsequent to the fermentation process, a thorough analysis of the wine was conducted in the laboratory. This analysis included the measurement of pH, volatile acidity, free and total SO_2 (sulphur dioxide), total acidity, alcohol content, reducing sugars, and density, all following the established OIV methodology.

3.4 Data Analysis

The average and standard error was computed for all the parameters analysed for each plot. To obtain a statistical comparison of these parameters a one-way ANOVA statistical test was performed with a significance level of 0.05. In the case of significant differences, means were compared using the Tukey Test (using R statistical program; RStudio Team 2019).

Image analysis was used to obtain the following parameters, canopy porosity, individual bunch projected area in laboratory conditions, the number of berries per bunch in laboratory conditions, and the surface temperature of the vine, the row, and the inner row with thermography. For the RGB images, (canopy porosity, bunch area, number of berries) a custom-made python script was used for colour thresholding, to automatically performed image segmentation (Victorino et al., 2022) .For the thermography images two polygons were selected on the upper canopy, on the lower canopy, on the row and on the inter row. Then the average temperature was calculated inside each polygon. For more information regarding these topics check the reference (Piazzoli., 2022).

4 Results and Discussion:

4.1 Spatial variability

As stated in chapter 3.2.1, the first part of this thesis involved understanding the vineyard's intrinsic spatial variability, in order to select plants from both plots (control and PV) with similar performances at year 0. To find the best smart points, it has been decided to create georeferenced Kriging maps through the program QGIS (QGIS Development Teams, 2023), as seen in subsequent images (Figure 14 and 15), of different parameters, such as trunk diameter, pruning weight, phenology, and the spurs number. The first two held greater importance among the data sets due to their robust and reliable nature. Phenology was considered less robust as it tended to be relatively uniform at the end of the phenological year, making it not the best example for indicating spatial variability. In the image, colour variations on the map indicate differences in the selected parameters. The colour changes from orange to dark green indicating the differences in the parameter, the dark green represent the higher values depending on the parameter itself. After thorough analysis of the merged data on the map, it was essential to validate the theoretical plot's reliability in the field. This involved checking for missing plants, wire structural defects, excessive slopes, and ensuring an adequate random selection by confirming an appropriate distance between the smart.

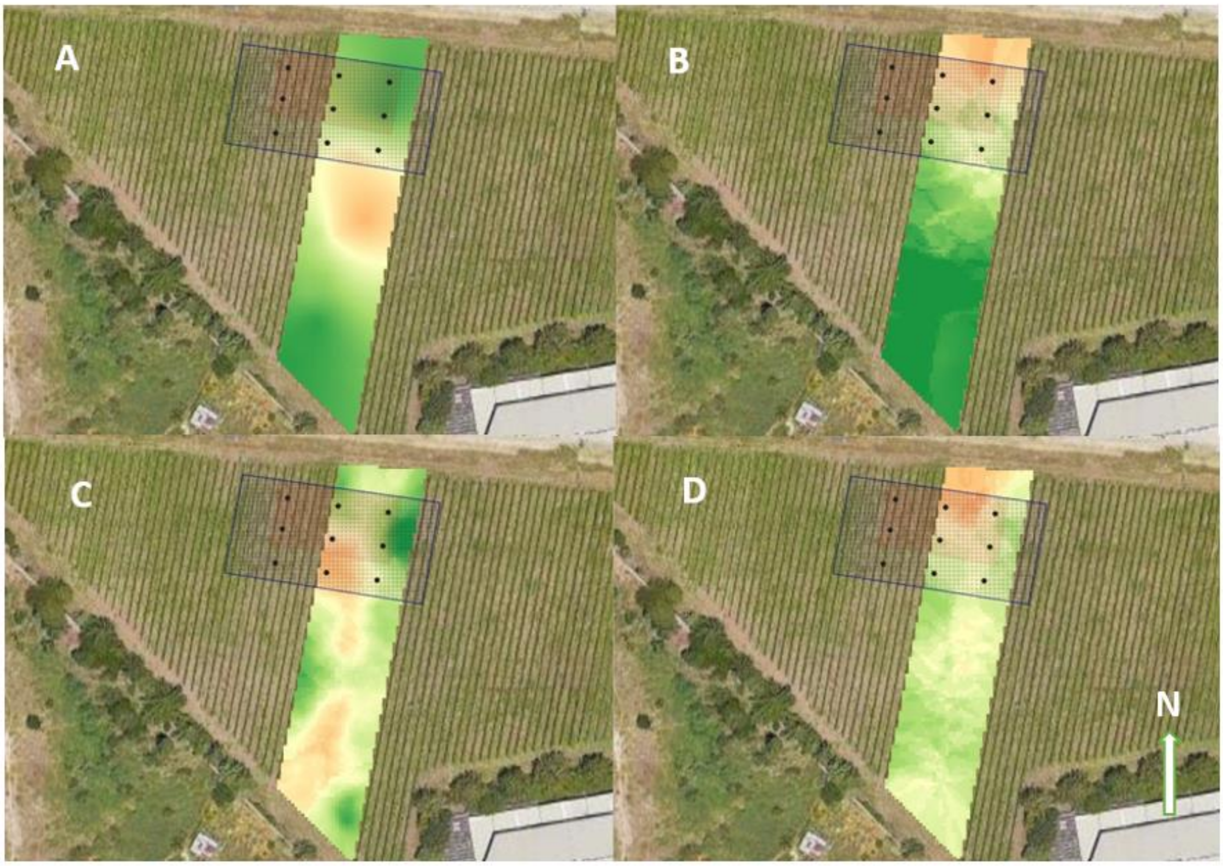

Figure 14 Aerial image of ISA vineyard with the Viosinho plot highlighted in false colour schemes as well as the location of the Agrivoltaic panel structure in a blue rectangle. Kriging map obtained using QGIS Smart-map plugin (Pereira et al., 2022). Black dots represent the foundation poles of the structure. Different parameters are analysed in each image, as follows: (A) pruning weight from the previous season, (B) Trunk diameter; (C) spur number and (D) phenology development near BBCH stage 13. The colour ranges from orange to dark green indicating the differences in the parameter, the dark green represent the higher values. Scale of 1:1000.

This approach enabled the map to provide an approximate assessment of vegetative development in the field, assisting in the selection of optimal vineyard areas, as depicted in the Figure 15. Upon the QGIS map were done, significant spatial variability, on all the parameters detected, such as pruning weight, trunk diameter, and the number of spurs per plant, phenology evolution, was observed in the Viosinho control area. Consequently, the decision was made to increase the number of Smart Points for the control area by one to account for this variability. These findings align with the patterns observed in Victorino et al. (2017) and Machado et al. (2018).

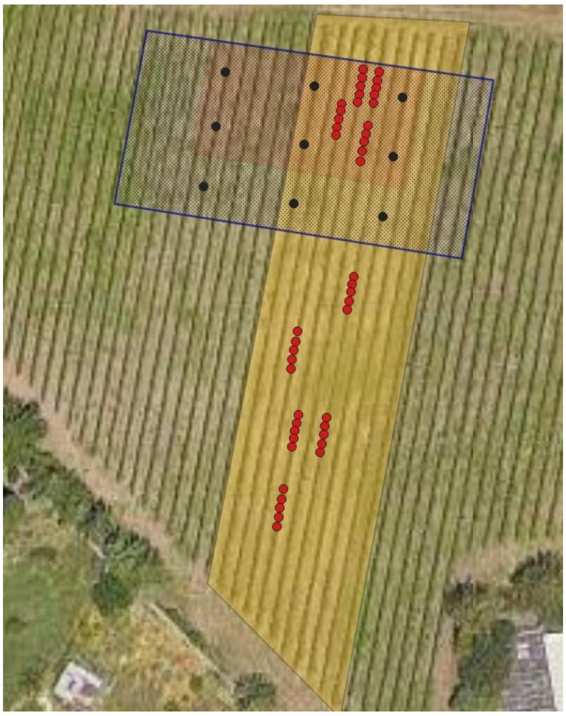

Figure 15: Kriging map. QGIS map, where are identified the Viosinho vineyard area, in the green trapezium, the smart point in the PV area, defined by the blue rectangle, and the control one below the first one. Scale of 1:1000. Lisbon, Portugal at 38°42'24.61" N 9°11'05.53" W

After this evaluation as is it showed in the Fig 15, four smart point has been decided for the PV area, identified by the blue rectangle, and five for the control, in the area below the rectangle itself.

4.2 Soil and Petioles analysis

The soil analysis was conducted in March 2023, as explained in the materials and methods. No statistical analysis was performed due to limited data availability, and the analysis aimed to assess the overall nutritional condition of the field.

Table 1: Biochemical parameters obtained from Viosinho soil analysis. Average ± standard deviation. The table indicates the different concentration level of nutrients and the general characteristics of the soil texture. N = 18

Parameter	**Viosinho PV**	**Viosinho Control**
pH	7.2 ± 0.1	7.4 ± 0
EC (mS/cm)	0.1 ± 0	0.2 ± 0
Soil texture	Clay	Clay
P_2O_5 (mg/kg)	83 ± 18.5	127.6 ± 25.8
K_2O (mg/kg)	228.6 ± 24.8	299.1 ± 31.4
OM (%)	2.8 ± 0.2	3.3 ± 0.2
Ca (mg/kg)	3934.5 ± 142.3	4879 ± 369.9
Mg (mg/kg)	1164.9 ± 47.2	993.9 ± 2.2
Na (cmol+/kg)	0.5 ± 0.3	0.3 ± 0.1
CEC effective (cmol+/kg)	30.2 ± 0.9	33.6 ± 1.7
Fe (mg/kg)	133.1 ± 6.1	133.4 ± 3
Cu (mg/kg)	14.4 ± 0.7	16.3 ± 0.4
Zn (mg/kg)	5.5 ± 0.2	6.2 ± 0.6
Mn (mg/kg)	313.9 ± 1.7	348.2 ± 22.7
B (mg/kg)	0.6 ± 0	0.7 ± 0.1

The analysis revealed an average pH of 7.2 and 7.4 for PV and Control, respectively, indicating a slightly alkaline soil. The soil is primarily clayey in texture. Overall, the soil shows high fertility, with most values being above the thresholds defined for highly fertile soils in DGPC (2006).

Table 2: Results obtained from the leaf petioles nutrient analysis of the two different plots. N = 4 samples of 50 petioles, obtained from 2 smart points of each plot.

Variety	**Plot**	**Na**	**K**	**Ca**	**Mg**	**P**	**S**	**Fe**	**Cu**	**Zn**	**Mn**	**B**
		mg/Kg										
Viosinho	PV	223	10550	14757	5490	5953	1652	38,4	11	36	50	35
Viosinho	PV	205	10451	14271	5726	6502	1647	51,8	12	32	37	34
Viosinho	CONT	157	14182	15805	5232	7454	1928	45,9	12	32	44	37
Viosinho	CONT	145	12938	14296	4700	6639	1778	76,6	11	34	40	36

The analysis of petioles is valuable for understanding the nutritional state of the plants and, if necessary, for initiating a fertilization program. Fortunately, most of the critical parameters show favourable values, showing an optimal nutritional status.

Of particular concern are the levels of potassium (K). According to the fertility classes of DGPC (2006), there is a slight deficiency of K overall which will be addressed with a post-harvest fertilization and over the next season to ensure that all nutrients are at an optimal level.

Overall, plant nutrition does not seem to be a limiting factor for this trial. However, this characterization is important not only to know the details of the soil biochemical composition but also, to compare with possible future analysis performed in the future and see if there is a significant impact of the panels on these parameters.

4.3 Phenology

To determine any differences between the plots throughout the plants growth, the various phenological stages were assessed, using the BBCH scale, up to the harvest day. It’s important to note that these assessments of growth stages were done through visual observations. Weekly pictures were taken to ensure a consistent and continuous record of these observations.

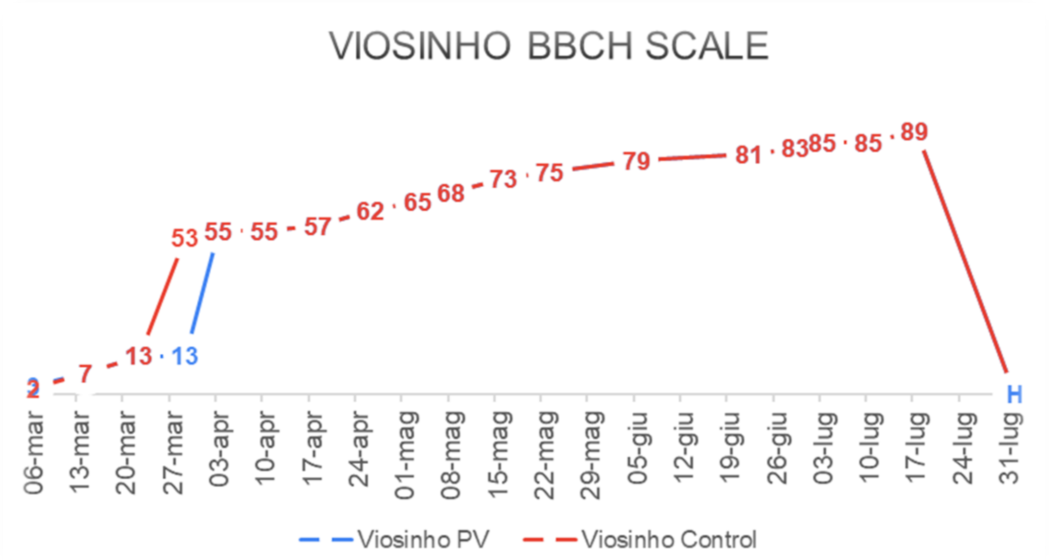

Figure 16:Phenological stage (BBCH scale) evolution from budburst until harvest for the Viosinho variety. Data obtained from the PV and Control plots.

The graphic of Figure 16 clearly shows that, apart from the initial weeks during bud burst and leaf growth, when there was a minor delay in the PV plot compared to the Control, the phenology progressed similarly for both plots after April 3rd. It's important to emphasize that all phenological stages happened earlier than usual for Lisbon wine region. The flowering period took place between April 17th and 24th, followed by the first appearance of bunches in the first week of May. After this, it was noticed that the ripening process took approximately a month and a half for veraison. But in the end, the harvest was done on the 1st of August. In fact, the delay was reduced but not entirely eliminated, as the harvest still took place about 2 weeks earlier than the norm in the European countries (Caffarra et al., 2012). This anticipation of the harvest period already discussed in the literature by (Mosedale et al., 2016; Parker et al., 2013; Santos et al., 2020; Yang et al., 2023) could be faced by the implementation of some adaptation measurements such as the agrivoltaic system, as a win to win strategy. The installation of PV panels could delay the phenological development of the plants, especially due to increased shading in the upper part of the vineyard, which could reduce photosynthetically active radiation (PAR) and temperatures beneath them. This delay can be noticeable from budburst onwards, as even a 2-degree difference could be significant during that period, potentially extending to the harvest itself. This prospective change is hoped to counteract the effects of climate change and achieve a more stable and consistent ripening process.

4.4 Vegetative development

In this chapter, the outcomes from the extensive dataset collected during various growth stages will be presented and discussed. The focus of the results is on assessing potential statistical differences to determine whether the two plots show different vegetative developments. One of the metrics used to assess plant vigour was shoot length. As mentioned in the materials and methods, the continuous growth of four representative shoots per smart point was evaluated (Fig. 17).

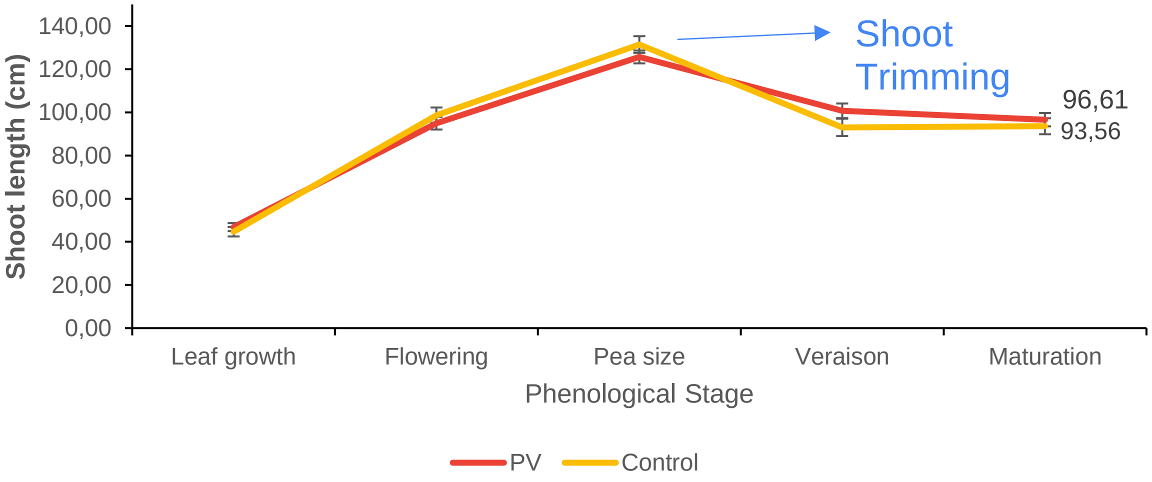

Figure 17: Evolution of the average shoot length (cm) with standard error during the season for the Viosinho variety. In red the PV shoot growth and in yellow the control one. N= 36

During the initial stage, which corresponds to leaf growth, it was observed that shoot length of the two plots was in the same range, approximately 46 cm and 44 cm. This indicates that the plants in both plots started their growth with similar intensity. By the flowering period, the shoots had doubled in length, reaching 100 cm in both cases. The shoots reached their maximum length during the pea size stage, peaking at about 131.4 cm. In this phase, a slight difference in length was observed in the control, but it was not statistically significant. Between the pea size and veraison stages, the shoots were trimmed (~ 20 cm above the last trellis wire), resulting in a sharp decrease in length to 100 cm. This remained the final length because the main shoots cannot grow without the apical meristem. Furthermore, upon examining the data in the Figure 18, it becomes evident that there are no statistical differences during any of the growth stages. This leads to the inference that, within this year, the plants exhibited relatively uniform shoot growth. It is important to note that shoot length is just one indicator of vigour. To assess other vegetative parameters, the total leaf area (Figure 18) and the exposed leaf area (Figure 19) were also measured.

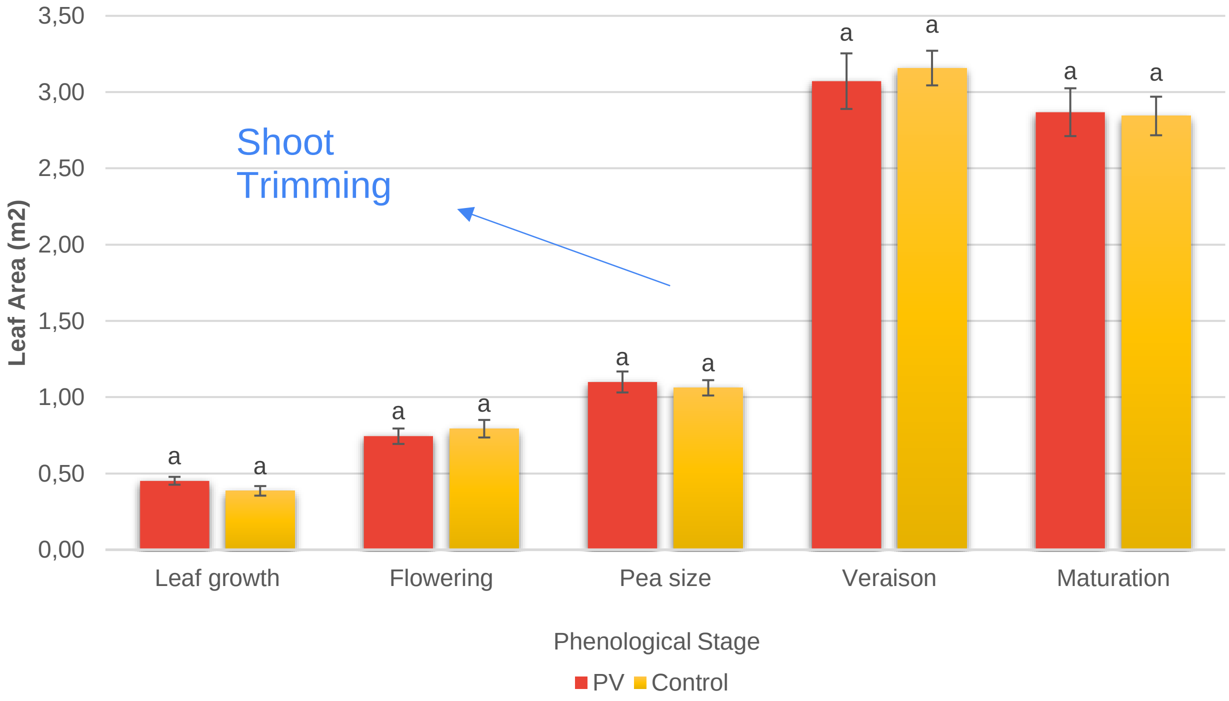

Figure 18: Average values of Viosinho leaf area (m^2) and Standard Error through the phenological phases. N= 46. The same letters ("a") indicate no statistical differences (p-value < 0.05). Shoot trimming was performed between the phenological stages pea size and veraison.

Leaf area growth began at the same intensity as shoot length, reaching approximately 0,45 m^2 for PV and 0,39 m^2 for control in mid-April. During the flowering period, it reached about 0,75 m^2 for both plots. Then it kept growing to reach about 1,1 m^2 at the pea size stage for both plots. After trimming, there was a significant increase in leaf area due to extensive lateral shoot growth that occurred between these two growth stages, reaching a peak of 3,1 m^2, which is roughly 200% more for both plots. Finally, during maturation, the leaf area was estimated at around 2,8 m^2. It can be assumed that this decrease is due to random damage and natural leaf senescence, which results in the loss of some of the lower leaves, or possibly some inherent variability of the used method.

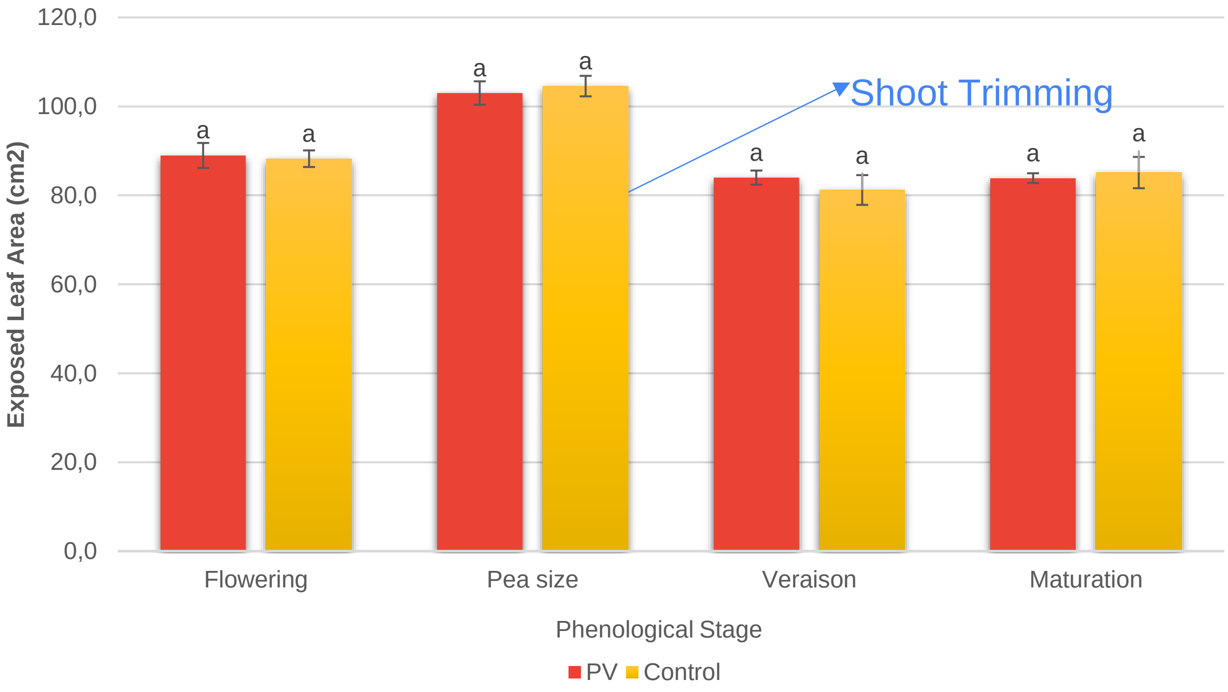

Figure 19 Average values of Viosinho Exposed leaf area (cm^2) and Standard error through the season. N=46. The same letters ("a") indicate no statistical differences (p-value < 0.05). Shoot trimming was performed between the phenological stages pea size and veraison.

Regarding the exposed leaf area (ELA), it should be noted that out of this group of analyses, it's the only one where data collection began during flowering. This choice was obvious since there wasn't a well-defined canopy structure during that period. The average ELA was evaluated to be around 89 cm^2 for both plots during flowering. At pea size it reached an area of approximately 103.5 cm^2. However, the trimming of the shoots significantly reduced the average ELA to values even lower than during the flowering phase around 84 cm^2 for the PV plot and 81.2 cm^2 for the control. It's important to emphasize that no statistical differences were observed between the two plots at any phenological stage. The ELA remained unchanged after that point, even though the canopy density changed. During maturation, values of 84 and 85 cm^2 were recorded for the PV and the control, respectively. This trend is in line with the data on shoot length and the leaf area. The outcomes in both cases reflect what was observed for ELA, displaying no significant statistical disparities between the two plots. Consequently, it can be inferred that the plants maintain a comparable level of vigour and growth rate throughout the season. This also leads to the assumption that they are likely accessing similar nutrient levels across various parts of the field (Dry & Loveys, 1998). It's worth considering the factors contributing to the decrease in shoot length and exposed leaf area observed between the pea-sized and veraison stages. This decline can likely be attributed to the trimming of shoots carried out during that timeframe. However, leaf area remains unaffected due to the lateral shoot growth that occurred concurrently. The last parameter analysed related to vegetative development was the canopy Porosity (figure 20).

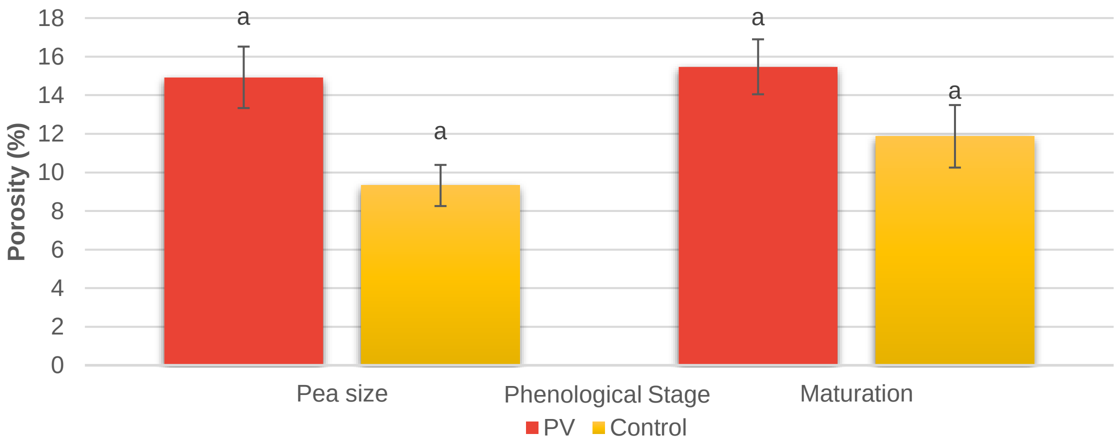

Figure 20: Viosinho canopy porosity percentage with Standard Error, during pea size and maturation phases. N= 90. The same letters ("a") indicate no statistical differences (p-value < 0.05).

Porosity is another method to measure how open the canopy area is, and it's also related to how much the grape bunches are exposed. As expected, the data doesn't reveal any statistical differences in this case. These findings align with what it was observed in the other canopy parameters. The Control consistently had a slightly denser canopy, as well as seen in the chart of figure 21. The porosity remains fairly consistent until maturation. For instance, the PV exhibited around 15% porosity during both the pea size and maturation stages. On the other hand, the control showed a slight increase, likely due to summer trimmings, from 9% to 11%. Nevertheless, these percentages don't raise concerns regarding bunches being overly exposed to the sun, in fact the literature show how the ideal canopy porosity, in order to have an appropriate bunch exposition for optimal maturation conditions, should be between 10- 20 % (Diago et al., 2019). Most importantly for this experiment, there were not statistically significant differences between the two plots.

All the mentioned parameters can be notably influenced by the future installation of solar panels. Shading effects from reduced solar irradiation (PAR) due to the panels may cause a decrease in overall plant vigour and specifically affect vegetative growth (Greer et al., 2010, 2011). Consequently, in the areas covered by solar panels, one may observe fewer and weaker shoots, tending to grow towards the more exposed sunlit areas. This will lead to a more noticeable difference between the plots (Archer & Strauss, 1989;. Greer et al., 2011). Furthermore, this emphasizes the importance of adjusting the inclination of the solar panels to achieve the optimal balance between PAR and the energy obtained. On the other hand, regarding cases of high porosity, and consequently high bunch exposure, where bunches would perhaps be too exposed and risk being damaged by the sun, with the presence of panels, this risk would be lowered.

4.5 Plant and soil water status

In this chapter, the evaluation of the vineyard's water status dataset throughout the season is presented. Figure 21 illustrates a gradual increase of water stress throughout the phenological stages, reaching the peak during maturation. It is important to consider that the photovoltaic area is located at the highest point of the vineyard, so it is more prone to water loss through percolation and leaching than the control area, consequently, the former is more likely to have higher water stress (Victorino et al., 2017).

As described in the material and methods, the vineyard employs a drip irrigation system managed to maintain water stress within specific parameters, after veraison, optimizing its benefits while mitigating the negative consequences of prolonged and excessive stress.

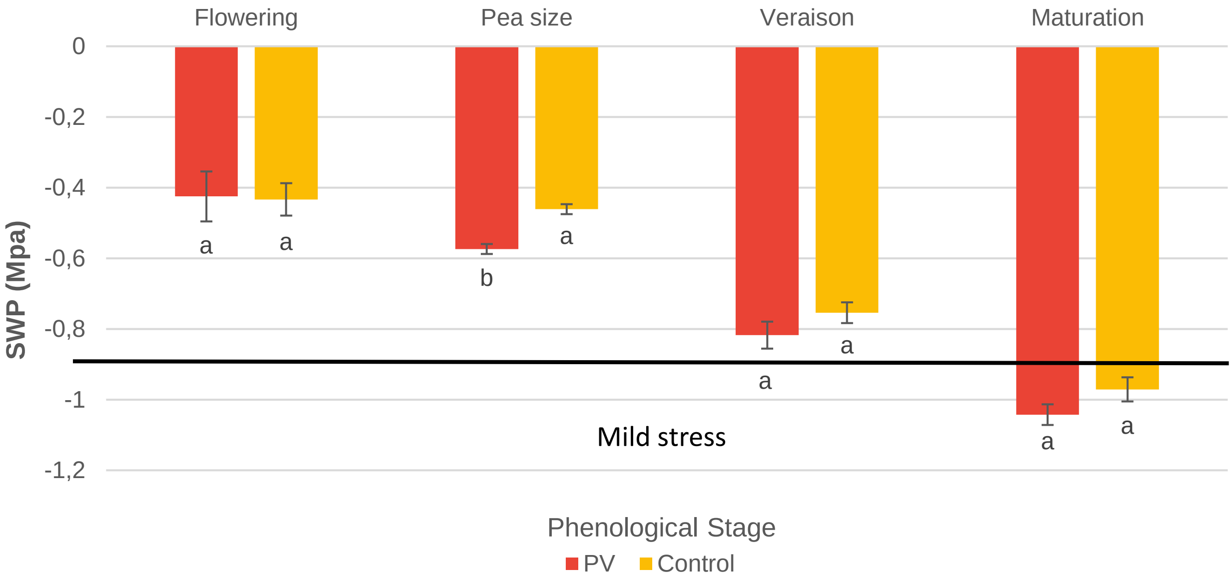

Figure 21: Evaluation of the average of Viosinho stem water potential (Mpa), and standard error, during the productive season. N = 18. Different letters (“a” and “b”) indicate statistical differences (p-value < 0.05).

In particular, the SWP was, during the flowering, around a value of -0.43 MPa for both plots and this is another confirmation, that during the first month, there were a common growth trend, between the plots as already seen in the other graphics. It's worth to notice that this trend is not true at the pea size phase, where it can be observed the only statistical difference. In this case the PV had a SWP -0.57 MPa compared to the -0.46 of the control, but both considered values of plant water comfort. After pea size the two plots presented statistically similar values. In fact, during the Veraison it was registered a SWP of -0.82 MPa for PV and -0.75 for the control, which increased respectively to -1.04 and – 0.97 MPa during ripening. On the 18th of July, during the maturation period, the SWP reached the minimum values that its completely in line with a good and qualitative maturation management of the vines, in order to stimulate the production of secondary products, such as aromas and polyphenols (G. A. Gambetta et al., 2020; Ojeda et al., 2002; van Leeuwen et al., 2019).

It's plausible to speculate that the introduction of solar panels could potentially nullify or even reverse the observed difference, even if the shape of the land is in slope and thus prompt to a higher water loss for the PV area. Indeed, the shading effect and the subsequent water re-accumulation provided by the panels will contribute to a better plant water status. Studies show how under such environment it's possible to save about 30% of water (Ferrara et al., 2023; Juillion et al., 2022) both from the less evapotranspiration due to the shading, and also because the solar panel can create a recycling system for the water. This one can evaporate on the bottom surface of the panels themselves, condensate and reprecipitate on the plants (Barron-Gafford et al., 2019).

4.6 Photosynthetic rate and stomatal conductance

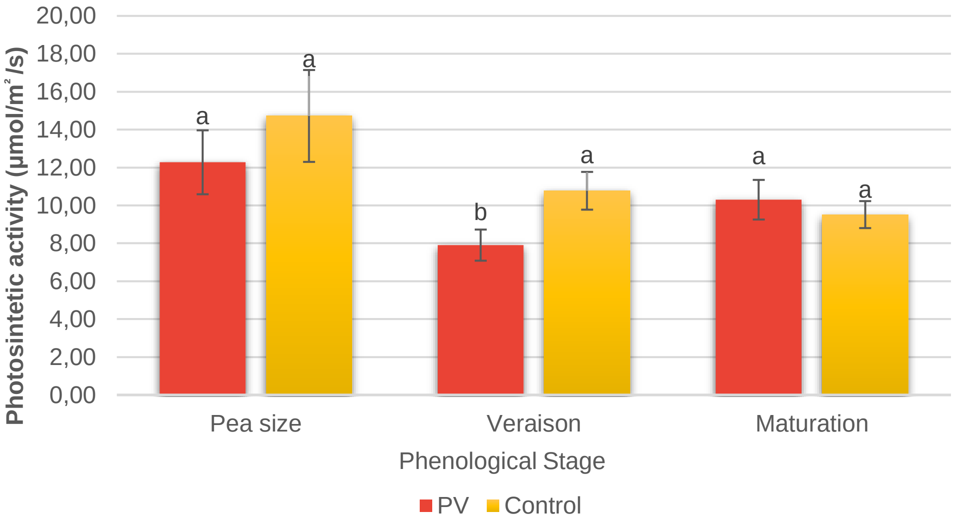

Figure 22: Average net photosynthetic activity (µmol of $CO_2/m^2/s$), with standard error, during the reproductive season, for the Viosinho variety. N = 18. Different letters ("a" and "b") indicate statistical differences (p-value < 0.05).

Shifting the focus to photosynthesis, no statistically significant differences are evident during the Pea size stage. However, a subtle trend is observed, indicating that the control group tends to display slightly higher values. This aligns with the common understanding that increased water stress usually leads to reduced photosynthesis, and vice versa. From the (figure 22) it's noticeable that for the measurements at pea size, the photosynthesis of the control group was slightly higher, around 15 μmol/m²/s, compared to the 12 (μmol/m²/s) of the PV. These values are also the highest among all the periods. Moving to the Veraison stage, the water stress increases according to SWP data, it’s observable a decline in photosynthesis activity to 11 μmol/m²/s for the control and to 8 μmol/m²/s for the PV showing a significant statistic difference. Surprisingly, this trend stops, showing same values, during the final maturation period, with a slightly higher value for the PV as compared to the control. Although there are no statistical differences, this could be due to a measurement error that might have affected all IRGA data. It's important to note that the machine faced some problems during the data collection period, potentially impacting the results of this analysis.

This trend is expected to intensify in the coming years, primarily due to the shading effect induced by solar panels. This shading effect is anticipated to decrease Photosynthetically Active Radiation (PAR) in the treated area, consequently impacting photosynthesis. Overall, it’s possible to anticipate statistical differences between the control group, exhibiting higher photosynthetic activity. It is essential to highlight that the PV settings must be aligned to allow the plants to receive a minimum of approximately 700-900 μmol/m²/s throughout most of the day to ensure that all processes related to photosynthesis activity are carried out, as mentioned in Chapter 2.5 (Cartechini & Palliotti, 1995).

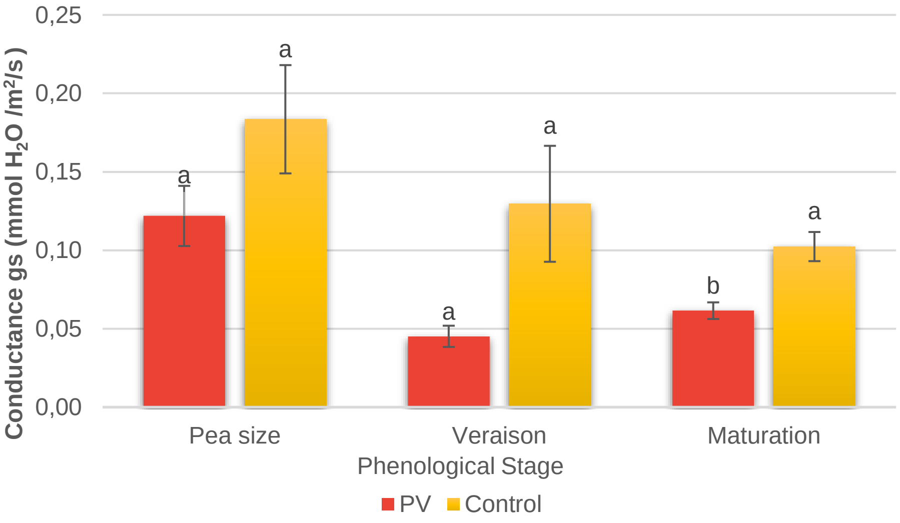

Figure 23: Average stomatal conductance of water vapor (mmol/m^{2}/s) and standard error, during the reproductive season (Pea size, Veraison and Maturation) for the variety Viosinho. N=18. Different letters (“a” and “b”) indicate statistical differences (p-value < 0.05)

Similar observations and hypotheses regarding photosynthesis can be extended to stomatal conductance. In terms of stomatal conductance, there is a consistent decline in values throughout the ripening period, which aligns with increasing water stress. For instance, during the pea size stage, stomatal conductance registered at 0.18 mmol/m^2/s for Control and 0.12 mmol/m^2/s for PV. These values then experienced a significant decrease, with PV reaching a minimum of 0.04 mmol/m^2/s and the control moving to 0.13 mmol/m^2/s. It's important to note that despite the fact that the average of control is more than twice as large than PV, there are no statistical differences, as observed in the subsequent phase, which had a narrower difference. This may be attributed to factors like the IRGA itself, the measuring method, and the higher standard deviation. During the maturation period, the average values settled around 0.10 mmol/m^2/s for Control and 0.06 mmol/m^2/s for PV, confirming the trend observed in all phases and the hypotheses mentioned earlier.

Once again, the installation of PV panels is anticipated to determine some changes between plots, mainly due to decreased PAR in the PV area. The reduction in solar irradiance, especially in the PV-treated zone, may influence stomatal behaviour and, consequently, stomatal conductance. Shaded conditions might prompt stomatal closure, potentially causing lower stomatal conductance in PV areas than in the more sun-exposed control areas (May & Antcliff, 1963; Powles, 1984). This reduction in stomatal conductance can affect gas and CO2 exchange as well as transpiration. These alterations in the microenvironment could introduce variability in stomatal conductance and the physiological responses of the plants (Lu et al., 2021). Hence, it's crucial to carefully manage the canopy and PV panel positioning throughout the day to optimize both objectives.

4.7 Canopy and Soil temperature

As it showed in the literature (*Grant, O. M. 2012)* the thermography it’s a helpful tool to evaluate the temperature on the field, and on the plants. But it could also be used as a water stress index or as air temperature indicator.

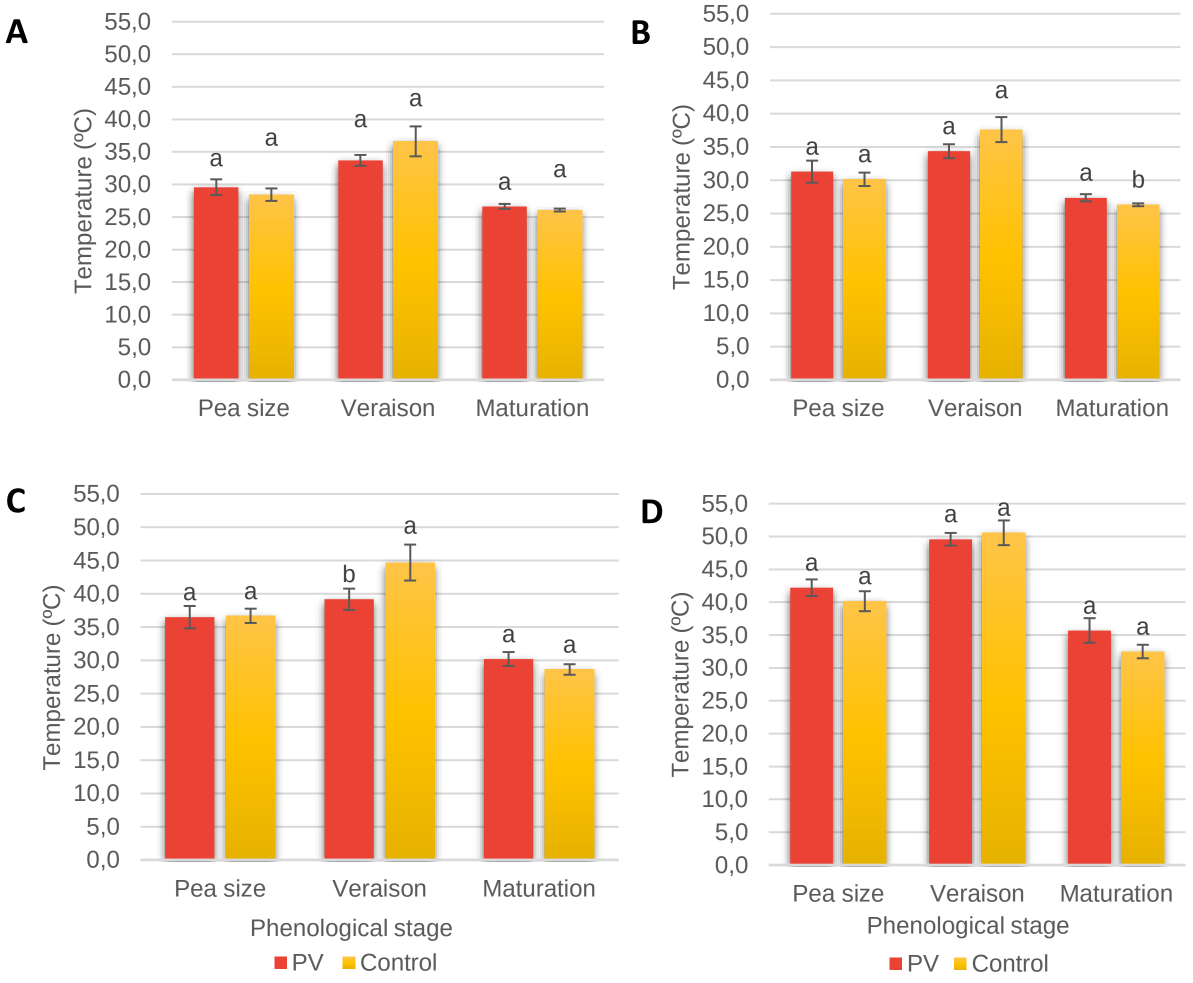

Figure 24: Average temperatures of the Viosinho upper (A) and lower canopy (B), and of the soil on the row (C) and interrow (D) using thermography. N= 18. Different letters ("a" and "b") indicate statistical differences (p-value < 0.05)

The graphics of figure 24 put in evidence how all the temperature measurements show the same trend, along the phenological stages between the two plots, without any statistical differences for almost all of the scenarios. The temperatures in the upper part of the canopy were slightly lower than the ones in the lower part because the higher proximity to the soil. It's interesting to note that the temperatures at maturation are lower than those at veraison. This might appear unusual, but in general, they align perfectly with the recorded temperatures of those days. For instance, on the 28th of June during veraison at 3 pm, the temperature was 33°C, whereas during maturation on the 26th of July, it was 28°C at the same time according to the meteorological station installed in the field. The temperature in the row and in the inner row shows the same pattern. The installation of the solar panels will surely decrease all the temperatures in the covered area, creating a widest difference between the values, in the canopy and in the row itself.

4.8 Bunch and berries detailed measures

Bunch and berries laboratory measurements were taken a few days before the harvest. This operation, described here as detailed measurements, aimed to assess the reproductive traits of the vines. This included measuring berry weight, rachis length and ramification number, and taking pictures with a camera to gather metrics related to the bunches, particularly bunch projected area and perimeter and to estimate the average number of berries per bunch.

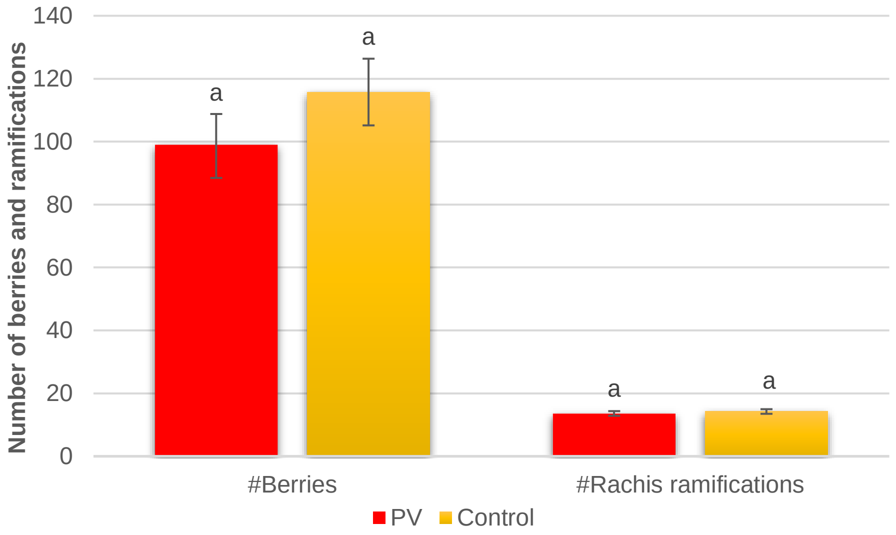

Figure 25: Average and standard error for the number of berries and the number of rachis ramifications, with the standard error. N= 45. Different letters ("a" and "b") indicate statistical differences (p-value < 0.05)

As shown in Figure 25, are not presents any statistical differences between the two plots. The number of berries is a crucial factor in understanding both yield and quality. Studies like Husfeld (1970), have demonstrated that, for the same weight, a higher number of berries contributes to better quality. This is because a higher number of small berries with a favourable pulp-to-skin ratio indicates higher quality compared to fewer but larger berries. Berries that are smaller in size have a higher concentration of essential nutrients and quality elements like sugars, acids, aroma starters, and polyphenols per berry. This makes them superior in quality when compared to larger berries (Luzio et al., 2021). On average, there were 99 berries per cluster for the PV group and 115.8 berries for the control group. Consequently, the weight of the berries was 167 g for PV grapes and 215 g for the control, resulting in an approximate weight per berry of about 1.68 g for PV and 1.85 g for the control (this measure is an approximation because is the result of the ratio between bunch weight, which includes the rachis, and berry number). The control plot had approximately 10% more bunch weight, but none of these differences were considered statistically significant.

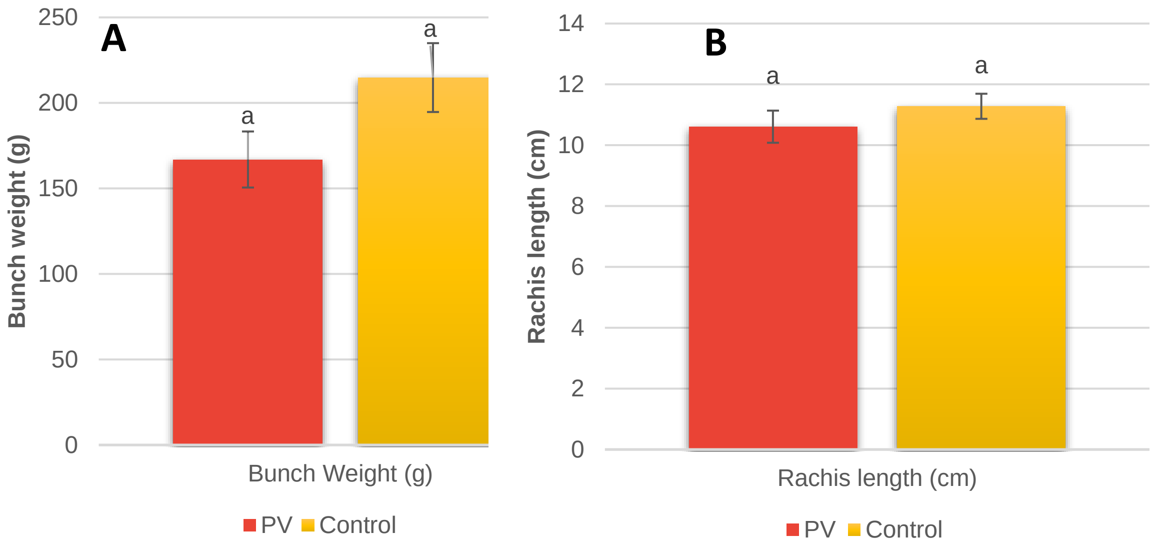

Figure 26: Viosinho Average values and standard error for bunch weight (A) and rachis length (B). Different letters ("a" and "b") indicate statistical differences (p-value < 0.05)

Figure 26 displays the rachis length and the bunch weight. The rachis results align with the trend observed for the berries, showing no significant differences between the two plots. The average rachis length for the PV plot was 10.6 cm, whereas for the control, it was 11.3 cm. Additionally, as showed in the previous figure, the average number of ramifications was 13.6 for PV and 14.2 for the control. However, it's important to note that determining the number of ramifications can be subject to some human error, especially at the lower part of the bunch where the ramifications are less clear. As already announced, the shadow effect of the PV could reduce the yield, impacting the number of bunches, berries and berries size (Archer & Strauss, 1989; Cartechini & Palliotti, 1995; Kappel & Flore, 1983). However, predicting the exact effects is challenging, as they will also depend on the water stress of the plants. Hypothesizing that the total amount of water available (form irrigation, precipitation and in the soil) will be the same for both plots throughout the year, a dual effect is expected. First, reduced insolation, especially after flowering, as it's a fundamental phase, could decrease the available energy for the plant, affecting cell differentiation and thus the maximum berry size, potentially resulting in sparser bunches (Kennedy, 2002; Korkutal et al., 2019; Ojeda et al., 2001). This effect could be viewed positively for varieties with high berry density, reducing infection rates and improving air circulation within the bunches. Second, regarding evapotranspiration and water availability, as already mentioned in the chapter 4.5, the area under the PV may experience reduced water loss due to increased shade and slightly lower temperatures.

Furthermore, there is a chance that water condensation on the PV surfaces could enhance water availability, which might result in larger berries. These effects might also increase the natural dropping of flowers and green berries. In fact when a vine lacks sufficient energy during flowering or the initial phase of fruit set, it tends to encourage the fall of unfertilised flowers and fertilised flowers that are not transformed into berries, in order to ensure the ripening of the remaining not fecundated flowers and the fecundated ones not transformed into berries (Boss et al., 2003). Therefore, the flowering and fruit set phases are crucial moments to ensure a good yield. It could be a good strategy to reduce the energy acquisition from the panels during those specific weeks. This helps avoiding carbon shortages in the plants and, consequently, minimizing flower drop.

4.9 Disease infection

In figure 27 are presented the average bunches affected by disease in general such as botrytis, rot or oidium, and the average severity of the infection in the affected bunches. In general, the bunches presented good health conditions, with around 1 affected bunch per plant for the PV and 0,5 for the control.

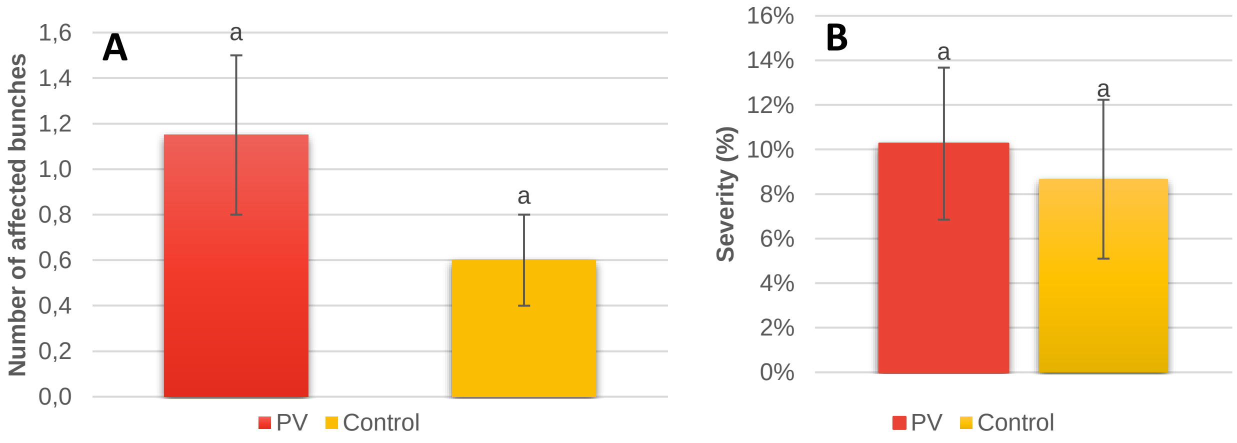

Figure 27: Average and standard error values for the number of bunches affected by diseases (A) and the severity disease percentage (B) at harvested *(N= 45). Different letters ("a" and "b") indicate statistical differences (p-value < 0.05)*

The severity, thus the percentage of infected berries per bunch, of disease was about 10 % of berries per affected bunch for PV and about 9 % for the Control, without statistically significant differences and confirming the good health status of the grapes.

In the figure 28 it's presented the average number of bunches eaten by the birds. During the harvest of each plant, bunches highly damaged by birds were identified. In the PV plot an average of 4 bunches per plant were observed with this issue, while only 1 bunch in average was observed for the control.

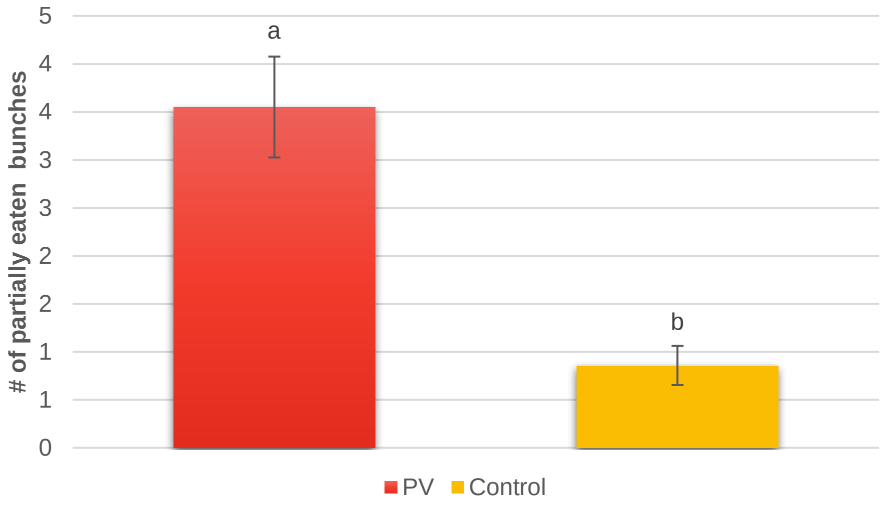

Figure 28: *Average and standard error for the number of damaged bunches by the birds. Only bunches with more than 50% of visibly eaten berries were considered. Different letters ("a" and "b") indicate statistical differences (p-value < 0.05)*

The number of damaged bunches is quite significant, especially considering that no protective measures were used. In this context, solar panels could potentially have an impact by postponing berry maturation for birds, which may reduce their access to the grapes (Ferrara et al., 2023; Mamun et al., 2022).

When considering future effects of photovoltaics, one can speculate that the differences between the two case studies might increase. This could happen for a number of reasons and will depend mainly on the parameters of the solar panels, such as the distance between them, their inclination, their height from the plants, their constituent materials and the average amount of solar irradiation received by each plant. Assuming a significant reduction in solar radiation, there could be several repercussions on yield and disease rates. For instance, the expected increase in shade due to solar panels might reduce photosynthetically active radiation (PAR) and relative humidity under the panels. The increase in humidity (Ferrara et al., 2023; Smart, 1985; Zahavi et al., 2001) could favour the reproduction of downy and powdery mildew and botrytis, ultimately possibly requiring more sprayings per year. There is the possibility that, due to the covering effect of photovoltaics, the plants will have less chance of being wetted directly by water and this could have a positive effect in terms of reaching the threshold for active fungal colonisation, for example, as the 10 mm rain rule for downy mildew (Gessler et al., 2011; Oliva et al., 1999). An additional consideration involves Esca disease. During the current year, approximately four plants in their rows succumbed to Esca. The anticipated rise in humidity under the solar panels might, quite probably, boost the disease's frequency, given its widespread occurrence in the field (Dinesh & Pearce, 2016; Ferrara et al., 2023; Zahavi et al., 2001). It's important to highlight that the presence of PV panels covering the plants may deter spore circulation and the spread of fungi. As mentioned in Chapter 4.8, a reduction in PAR could result in decreased bunch compactness and, consequently, lower infection rates. Therefore, the future assessment of the solar panel's effect on diseases is enveloped in uncertainty, a topic that future research endeavours will strive to elucidate.

4.10 Yield and yield components

Regarding the number of bunches (Figures 29 and 30), no significant differences were observed. The PV plants showed an average of 10.7 bunches, while the control ones showed 11.4. To better understand the intrinsic variability, Figure 30 shows the specific bunch production per plant.

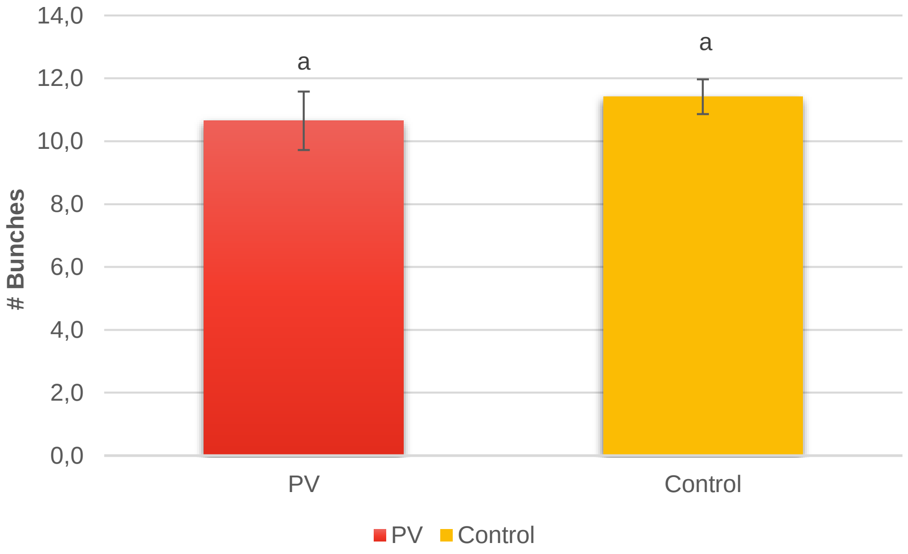

Figure 29: Average bunch number for the Viosinho variety. In red the PV smart points and in green the average of the control one, both with the standard error. N=45. *Different letters (“a” and “b”) indicate statistical differences (p-value < 0.05)*

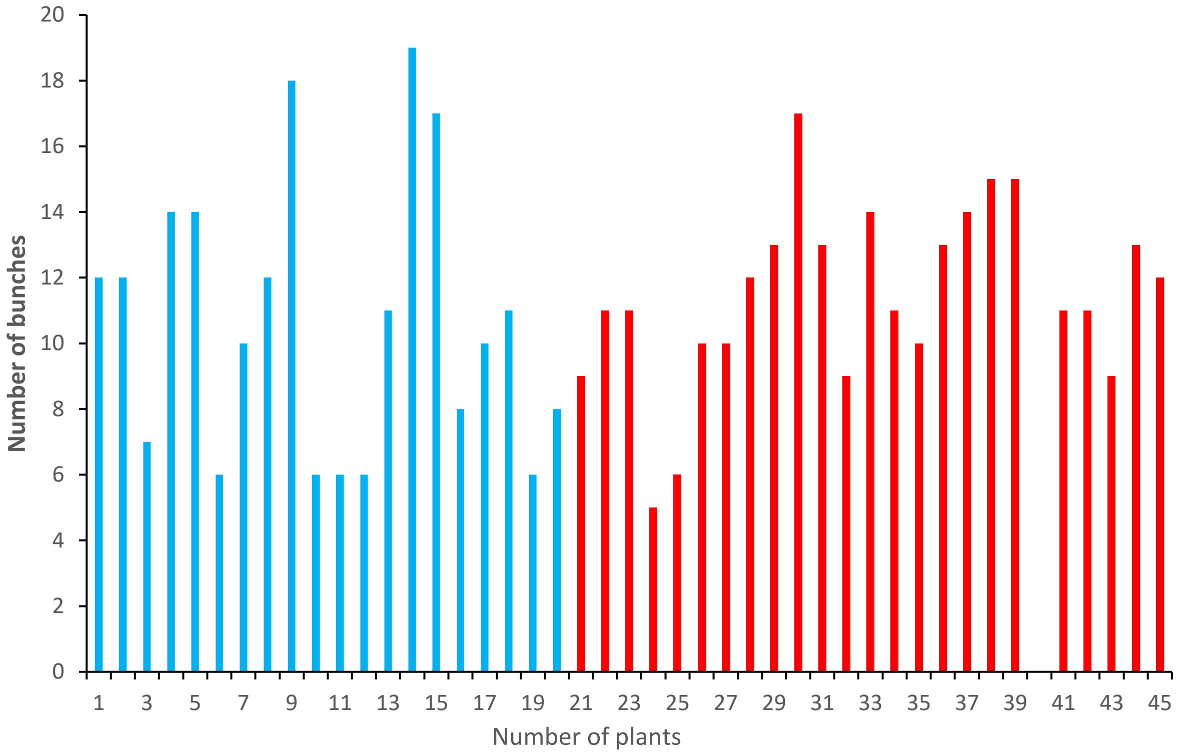

Figure 30 Bunch number per plant for the two plots of variety Viosinho (light blue: PV plot; red: Control plot).

The graphic highlights the yield variability present among the plants. For the PV, there is a fluctuation from a minimum of 6 bunches to a maximum of 19, and for the control, it ranges from 4 to 17. It's notable that there's a slightly higher fluctuation for the PV plot compared to the control, although the intrinsic variability is similar. (The fact that it seems to be a tendency for higher yield in control, while the number of bunches is the same indicate that the difference might be in bunch size. However, this difference is not significant, and it should be considered only as a trend).

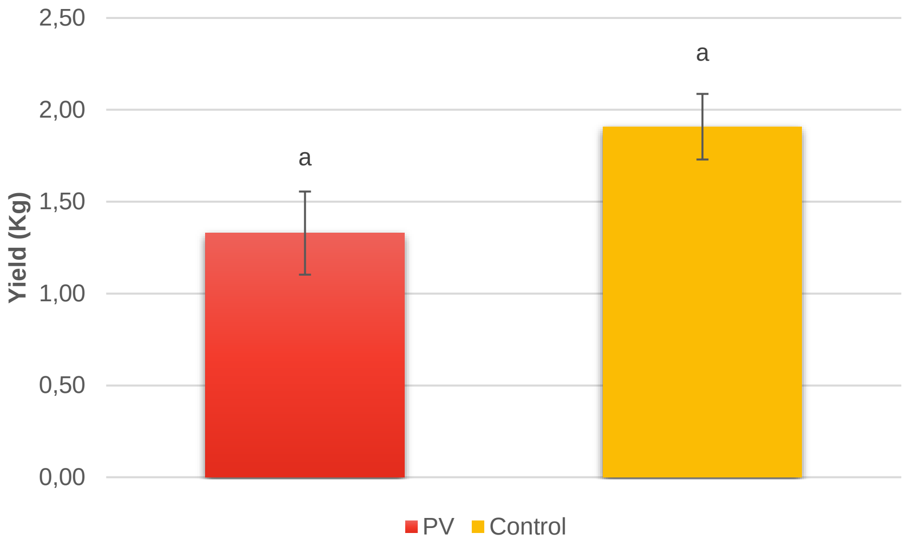

Figure 31: Viosinho average yield per Smart point. In green the average of all the PV smart points and in red the average of the control ones, both with the standard error. N=45. *Different letters ("a" and "b") indicate statistical differences (p-value < 0.05)*

Figure 31 represents the average yield per plant, which is 1.33 kg for PV and 1.91 kg for the control. Despite the control plot showing approximately 30% higher yield per plant, this difference is not statistically significant. It's important to note substantial variability within the smart points, with some plants visibly weaker or stronger, exhibiting varying vigour and yield. This variability is directly reflected in the high standard deviation for each plot. As shown in Figure 32, the average yield per plant is quite variable, with some outliers for both plots. In the PV, the most productive is plant 14, which yielded 4 kg, and in the control, plant 37 produced 4.5 kg. On the other hand, the weakest plants are plant 2 for the PV and plant 24 for the control, neither reaching 1 kg of yield. In any case, despite a trend towards slightly higher yield in the control, there is no statistical difference. It's also worth noting that there appears to be a tendency for a higher yield in the control group, even though the number of bunches is the same. This suggests that the difference might be related to bunch size. However, it's important to emphasize that this difference is not statistically significant and should be viewed as a mere trend.

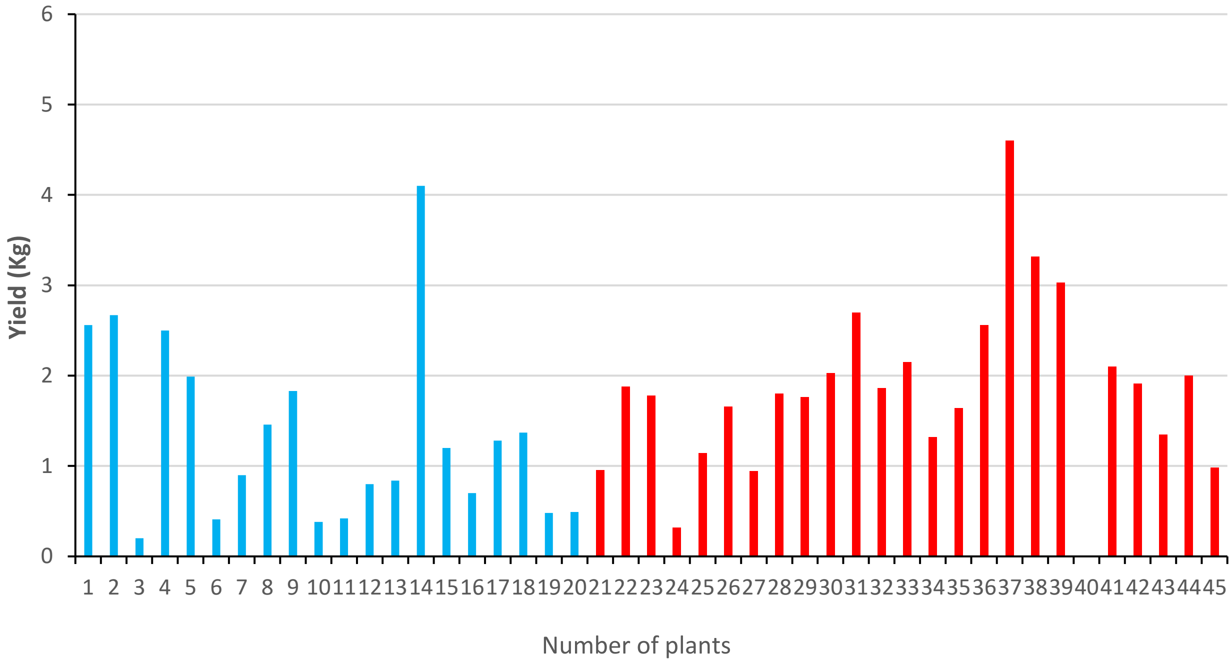

Figure 32 Viosinho yield per plant. In blue the yield for the PV and in red the one for the control. N=45

The effects of the PV on the yield could, in the first place, decrease the vine's vigour, leading to an increased competition between vegetative and reproductive growth cycles. Consequently, this might make it harder for the vine to maintain the same levels of yield (May & Antcliff, 1963; Scafidi et al., 2013). Indeed, as already explained in chapter 4.8, less irradiation may result in smaller and fewer berries. However, there is also the possibility that more water availability may increase the period of time in which the plant has optimal conditions for gas exchange and thus the daily activity of photosynthesis (Ferrara et al., 2023). Perhaps this could ensure that minimum daily photosynthesis activity is achieved, thus reducing the possibility of a reduction in yield.

Lowering the maximum daily temperature may also reduce sunburn occurrence, potentially increasing final yield. Unfortunately, this is a measure that has not been taken into account (Barron-Gafford et al., 2019; Dinesh & Pearce, 2016; Santos et al., 2020). This parameter was not evaluated this year because summer temperatures were mild and, overall, no significant sunburn losses were recorded. However, it will be an extremely important topic to address in other years with more drastic heat waves or higher temperatures overall. Furthermore, as mentioned in the previous sub chapter, the altered microclimate under the solar panels might increase the incidence of certain diseases which may affect final yield (Barron-Gafford et al., 2019; Mamun et al., 2022; Smart, 1985b; Williams & Ayars, 2005). Consequently, the exact future impact of solar panels in this situation remains uncertain. This uncertainty increases, in part, because the effects on production they can become more noticeable in the year after their installation (the second year of production after the start of the shading effect). This is due to the fact that the inflorescences differentiation halts around August and resumes in the subsequent spring. This means that production for the coming year is mostly determined by the number of inflorescences already present in the buds during the current year, which can be altered by temperature and radiation conditions, affected by the PV.

4.11 Oenological parameters

The oenological parameters were evaluated doing the analysis aimed at defined maturation trend, starting from a sample of 100 berries, the must and the wine characteristics. Those analysis were focused on the main oenological parameters such as the Brix, the pH and the acid content.

4.11.1 Berry sampling analysis

As can be seen in table 3, the evolution of the main metabolites was constant. There is a slight tendency, in accordance with the vegetative and reproductive growth during the season, for PV to be a little earlier in ripening than the control, but it is also clear that this tendency has no relevance, and furthermore is almost null at harvest. On the other hand, there is a slight tendency for the PV berry must to have a lower total acidity than the control. No statistical analysis of variance was performed for these parameters, as the berry harvest was destructive and accurate sampling would have influenced the final yield too much. Ripening proceeded fairly steadily over time (Atauri et al., 2017; Coombe, 1995; Tomasi et al., 2011; Yang et al., 2023).

Table 3: Results obtained from berry composition analysis obtained from 100 berry samples collected in the vineyard, for both PV and control plots, at different days during ripening.

Plot	**Date**	**Weight of 100 berries (g)**	**Wine must (100ml)**	**Brix (%)**	**Probable alcohol strength (% vol)**	**pH**	**Total acidity**
Control	03-July	132,4	74	12,8	8,0	2,77	20,4
Control	10-July	187,2	112	16	10,0	2,91	12,6
Control	17-July	190,0	96	18,2	11,4	3,06	8,85
Control	24-July	200,6	104	20	12,5	3,17	6,98
PV	03-July	132,8	79	12,7	7,9	2,82	19,0
PV	10-July	164,8	106	16,2	10,1	2,95	11,1
PV	17-July	162,8	88	18,3	11,4	3,07	9,3
PV	24-July	201,8	106	20,4	12,7	3,27	5,66

The berries of the Control and PV increased their weight by 44%, in 4 weeks, following a fairly constant increase over time, except for a moment of delay during the weeks between 10th and 17th July, when berry growth was almost zero or even regressed. In fact, by checking the weather station it is possible to extrapolate that, due to the lack of rain in July, and the high temperatures, on the 10th, reaching 35°C, and the 32° C on the 17th, the ripening stopped briefly as it can be observed in Table 3, with the lack of increase in the weight and slight decrease in must volume. The volume of the berries must followed exactly the same trend as the weight of the berries, with an even more evident drop between the same dates. In fact, it fell by around 15% and 17% for Control and PV respectively, finally reaching the last value of 104 and 106 ml of must in the week before the harvest. It's also possible to observe that the final volume of berries must is more or less the same as on 10 July. As far as the sugars are concerned (Brix), the increase was quite fast between the 3rd and 10th of July, going up by about 20 per cent for both. After that period, it continues to go up steadily by about 2º brix every week, reaching the final values of 22.5 and 22.4º Brix for Control and PV, respectively, at harvest. These values correspond to 14.1 and 14 probable alcohol, which is somewhat high for a white wine, but not uncommon in southern Mediterranean regions such as Portugal. It is also confirmed that the differences between the plots cancelled out at the end of ripening. In addition, while there was a slight tendency for the PV plot to experience slightly higher stress than the control at some stages (Fig. 23 and 24), the difference was not significant enough to affect berry composition in the respective plots. Finally, some differences regarding the pH and total acidity might be relevant. As expected, pH gradually increased to approximately 3.4 due to malic acid respiration. Although there was a slight difference observed throughout the ripening period between the two field areas, this distinction wasn't noticeable at the end of ripening. These differences are most evident when observing the total acidity, in the week prior to harvest, which following a decreasing trend reached final values of 7.0 and 5.7 g tartaric acid/L for Co and PV. These values are also very interesting because they changed greatly and unexpectedly between the week before the harvest and the must obtained from the harvest itself. In particular, the total acidity of the control dropped from 7 to 5.3 g tartaric acid/L, and the PV from 5.7 to 5.0 g tartaric acid/L. This highlighted a wide contrast of values that can only be justified by looking at the number of samples. Analysing 100 berries may not precisely represent a representative statistical sample. The small quantity of berries could potentially affect the analysis. Hence, increasing the number of berries for analysis in future years is recommended to ensure more accurate results.

Table 4 . Results obtained from the must analysis of Viosinho variety, on both plots, harvested on August 1st 2023.

Plots	Brix (%)	Alcohol strength	pH	Total acidity (g/l tartaric acid)
Control	22,5	14,1	3,4	5,3
PV	22,4	14.0	3,4	5,0

Finally, the total yield was about 37,5 Kg for Control and 26,5 Kg for the PV. It's important to note that this wide difference is mainly because the Control has one smart point more than the PV.

4.11.2 Final Wine Analysis

From the micro vinification, of all the Smart Point Viosinho grapes, separated in PV and Control, as explained in the Materials and methods. Table 5 shows the results of the analysis performed on the resulting wine.

Table 5: Viosinho wine analysis for the two studied plots, after alcoholic fermentation.

Date	Plot	pH	Volatile Acidity (g/L acetic acid)	Total Acidity (g/L ac tart)	Alcohol at 20°C (%vol)	Reducing sugars (g/L)	Density (g/L)
25-ago	Control	3,43	0,29	6,64	14,2	0,7	992 at 25°C
25-ago	PV	3,45	0,32	6,45	14,0	0,8	992 at 25°C

From its lab analysis, what was assessed earlier on the must analysis gains more reliability. Firstly, it is immediately apparent that the quantity of grapes for the sample is indeed subject to a high range of error, in fact some values are quite different in the two tables. Apart from the differences observed during maturation, in the table 5, which represents the analysis parameters of the wine after alcoholic fermentation, it can be observed that the analysis of the wines obtained from the two plots present similar results.

The final alcoholic degree is around 14 degrees, probably, as already mentioned, a little too high since it is a white wine, although it is increasingly common to have such values in these years, it was likely harvested too late. The same goes for the pH, which reaches final values of 3.4 for both PV and Control, is perfectly in line with those in table 3 and 4 (must of berry and wine analysis), although the total acidity is a little surprising. In fact, it presents 1.30 g/L more tartaric acid than the final must data for the control and 1.45 g/L more for the PV. Such a high increase is rare but possible and could be due to the acid products obtained from alcoholic fermentation such as succinic acid, acetic acid, pyruvic acid and others, even if in very low quantities giving to the determination of total acidity values was the one with the greatest fluctuation (Thoukis et al., 1965). The high variability indicates that for the next years it would be a good practice to increase the number of samples, while trying to minimize the number of destroyed berries.

In the coming years, the installation of photovoltaic panels is likely to significantly impact grape characteristics in our two case studies. Previous research suggests that some changes will occur in the oenological characteristics. For example, in Ferrara et al., (2023), Juillion et al., (2022) and Malu et al., (2017) increased shade from PV panels can reduce malic acid respiration, resulting in a decrease in pH and an increase in total acidity. This can help mitigate the effects of climate change, including high temperatures, elevated sugar levels, and low acidity, potentially enhancing the quality of the final product (Ferrara et al., 2023; Fraga et al., 2012; Santos et al., 2020). In terms of sugars and potential alcohol content in the wine, in line with the earlier discussion, a reduction in these components is anticipated in the PV plot due to decreased photosynthetic rates. However, accurately estimating the extent of this reduction remains challenging. Predicting the effect on berry weight is challenging, mainly because it depends on irrigation and several other factors, as discussed earlier. However, assuming both plots have equal water availability, it’s possible to anticipate a dual impact. Less sunlight can lower available energy, influencing cell development and, consequently, the total number of cells in the berries (Rogiers & Clarke 2013). This could result in sparser bunches and smaller berries, leading to a higher pulp-to-skin ratio and an overall improvement in quality due to higher metabolite concentration. However, it's essential to note that water availability might also influence berry size, potentially causing larger berries due to more dilution. Understanding the precise impacts on both the size and quality of the berries is difficult due to conflicting factors, making it impossible to predict a precise result. It's clear that achieving the right harmony between the efficiency of solar panels and the plant growth rate is crucial for overall quality (Santesteban et al., 2011; Wang et al., 2003).

5 Conclusions

This study aims to comprehensively examine the spatial variability between a control plot and a plot where an Agrivoltaic structure will be installed. Because the two different plots need to be physically separated, it is expected that some inevitable variability is present. This analysis covers various aspects, including plant growth and development in terms of vegetation and phenology, plant water status, yield, grapes detailed measurements and wine composition. In terms of phenology and vegetative development, no significant differences were observed between the plots. The two studied plots exhibited consistent and aligned development throughout the vegetative and reproductive phases, except for the first few weeks, where the PV showed a slight advance in phenology, around budburst. Regarding water availability, a slightly higher deficit was noticed in the upper part of the vineyard, where the PV panels will be installed, and a difference statistically significant appear during pea size. The slight water deficit in the PV area also impacted photosynthesis activity and stomatal conductance, with statistically significant differences, especially during the maturation stage. Concerning yield, no statistically significant differences were observed between the plots. As for the other parameters, the berry sanitary conditions were generally good for both the plots and all the difference were not statistically significant. Interestingly, the control plot experienced fewer losses due to bird activity, which could have had a slight impact on the final yield, as birds were the main reason for PV yield losses. Regarding berry characteristics, such as number and weight, no notable differences were observed. Lastly, there were no statistically significant differences in the must and wine quality characteristics between the two plots, indicating that both plots behaved similarly in this regard. However, it should be noted for future reference, that the PV plot has a trend to be slightly more stressed than the Control plot, even though in most cases the difference is not statistically significant.

With this work, the variability between the two plots was analysed in detail, no statistical differences emerged in the main vegetative and reproductive parameters, with only some slight differences in water status and the firsts phenological stages, meaning that the smart points were well established in order to assess the future impact of solar panels. Most importantly it creates a detailed basis for the agrivoltaic research studies to be done considering the spatial variability in the field highlighting various aspects including plant development, water availability, yield, grape, and wine quality. Further research and long-term monitoring will provide valuable insights into optimizing the coexistence of solar energy production and vineyard cultivation. Furthermore, the studies of critical phenological periods should be evaluated in order to define the best balance between the energy production, the plant optimal growth conditions and the overall wine quality.

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7 Annexes

Table 6: ANOVA results obtained for the vegetative parameters data shown on chapter 4.4, 4.5, 4.6 results where each parameter was compared between PV and Control for the Encruzado variety at different phenological stages. Df (Degrees of freedom), Sum, Sq Mean (Mean square), Sq F value, Pr (> F) (P-value). The parameters analysed were LA (Leaf area), ELA (Exposed leaf area), Porosity, SWP (Stem water potential), Photo (Photosynthesis rate), Cond (Stomatal conductance).

Parameter	Variety	Stage	Df	Sum	Sq Mean	Sq F value	Pr (>F)
Shoot length	Viosinho	Maturation	1	83	82.82	0.434	0.515
LA	Viosinho	Leaf Grow	1	0.215	0.2147	1.728	0.197
LA	Viosinho	Flowering	1	0.088	0.08825	0.467	0.499
LA	Viosinho	Pea Size	1	0.23	0.2297	0.655	0.424
LA	Viosinho	Veraison 1	1	0.77	0.7704	1.219	0.277
LA	Viosinho	Maturation	1	0.001	0.0014	0.002	0.968
ELA	Viosinho	Flowering	1	6	5.86	0.049	0.825
ELA	Viosinho	Pea Size	1	27	27.04	0.2	0.657
ELA	Viosinho	Veraison 1	1	84.9	84.89	2.656	0.111
ELA	Viosinho	Maturation	1	17.1	17.10	0.775	0.384
Porosity	Viosinho	Pea Size	1	349.1	349.1	9.116	0.00425 **
Porosity	Viosinho	Maturation	1	144.3	144.34	2.643	0.111
SWP	Viosinho	Flowering	1	0.025	0.0250	0.113	0.742
SWP	Viosinho	Pea Size	1	5.650	5.650	31.09	4.18e-05***
SWP	Viosinho	Veraison 1	1	1.792	1.7921	1.801	0.198
SWP	Viosinho	Maturation	1	2.272	2.2721	2.385	0.142
Photo	Viosinho	Pea Size	1	26.5	26.54	0.617	0.444
Photo	Viosinho	Veraison 1	1	89.7	89.70	5.087	0.0294*
Photo	Viosinho	Maturation	1	6.8	6.847	0.409	0.526
Cond	Viosinho	Pea Size	1	0.01688	0.016878	2.114	0.165
Cond	Viosinho	Veraison 1	1	0.0778	0.07782	3.984	0.0524*
Cond	Viosinho	Maturation	1	0.01855	0.018551	12.77	0.000886***

Table 7 ANOVA results obtained for the thermography parameters data shown on chapter 4.7 results where each parameter was compared between PV and Control for the Viosinho variety at different phenological stages. Df (Degrees of freedom), Sum, Sq Mean (Mean square), Sq F value, Pr (> F) (P-value). The parameters analyzed were: The temperature of the lower canopy (LC), upper canopy (UC) and the Row and Inter row temperature.

Parameter	**Variety**	**Stage**	**Df**	**Sum**	**Sq Mean**	**Sq F value**	**Pr (>F)**
Thermography (Lowe canopy- LC)	Viosinho	Pea size	1	5.82	5.825	0.855	0.369
Thermography (Lowe canopy- LC)	Viosinho	Veraison	1	47.02	47.02	4.428	0.0515
Thermography (Lowe canopy- LC)	Viosinho	Maturation	1	4.976	4.976	8.78	0.00916 **
Thermography (Upper canopy- UC)	Viosinho	Pea size	1	5.87	5.870	1.293	0.272
Thermography (Upper canopy- UC)	Viosinho	Veraison	1	37.93	37.93	2.627	0.125
Thermography (Upper canopy- UC)	Viosinho	Maturation	1	1.392	1.3922	3.629	0.0749
Thermography (Row)	Viosinho	Pea size	1	0.18	0.183	0.02	0.888
Thermography (Row)	Viosinho	Veraison	1	135.4	135.43	5.177	0.037 *
Thermography (Row)	Viosinho	Maturation	1	11.11	11.107	2.949	0.105
Thermography (Inter row)	Viosinho	Pea size	1	18.8	18.76	0.634	0.438
Thermography (Inter row)	Viosinho	Veraison	1	4.3	4.273	0.2	0.661
Thermography (Inter row)	Viosinho	Maturation	1	45.66	45.66	3.239	0.0908

Table 7 - ANOVA results obtained for the yield and yield components data shown on chapter 4.8, 4.9, 4.10, 4.11 results where each parameter was compared between PV and Control for the Viosinho variety at different phenological stages. Df (Degrees of freedom), Sum, Sq Mean (Mean square), Sq F value, Pr (> F) (P-value).

Parameter	**Variety**	**Df**	**Sum**	**Sq Mean**	**Sq F value**	**Pr (>F)**
Yield	Viosinho	1	2.81	2.8090	2.927	0.0943
Bunches	Viosinho	1	1.1	1.068	0.073	0.788
Bunch Weight	Viosinho	1	25486	25486	3.176	0.0818
Bunches affected	Viosinho	1	3.36	3.361	2.049	0.16
Intensity	Viosinho	1	0.0025	0.002542	0.083	0.775
Bunches more than 50% eaten	Viosinho	1	74.28	74.28	22.72	2.61e-05 ***
Rachis Weight	Viosinho					
Rachis length	Viosinho	1	4.99	4.988	1.03	0.316
Ramifications	Viosinho	1	4.6	4.551	0.36	0.552
Berries	Viosinho	1	3102	3102	1.291	0.262
Berry Weight	Viosinho					
Lost Yield	Viosinho	1	0.2196	0.21956	17.93	0.000122 ***