



VITICULTURE ORIGINAL RESEARCH ARTICLES

Minimising sunburn necrosis on *Vitis vinifera* L. ‘Riesling’ grapes by defoliation, photo- and thermal protection

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ABSTRACT

Sunburn on grapes has emerged as an economic concern in recent decades. The phenomenon can be attributed to climatic changes, characterised by elevated air temperatures and intense solar radiation, leading to increased crop failures as well as quality losses of wines. This study aimed to evaluate comprehensively selected preventive strategies for the sunburn-sensitive, white cultivar ‘Riesling’. To this end, the impact of the timing of bunch zone defoliation on sunburn necrosis within three wine-growing regions in Central Europe, as well as the application of sunscreens onto grapes and shading by protective nets at one of these sites, were visually assessed in the contrasting growing seasons 2021 and 2022, respectively. Early defoliation between the end of flowering and fruit set decreased sunburn necrosis severity by down to 59.6 % in comparison to late defoliation at bunch closure across the two years. Furthermore, rot severity was reduced by down to 85.3 % in comparison to no defoliation across both growing seasons. The application of lime onto grapes following late defoliation diminished sunburn damage by 41.9 % across both experimental years, while kaolin showed no effect. Combining early defoliation with application of lime revealed an increased effectiveness of 79.2 % in comparison to late defoliation within one growing season. Different protective nets were able to lower sunburn damage within each growing season, but the black, small-meshed shading net with the highest shading factor investigated revealed the highest effectiveness of 63.7 % across both experimental years. However, the effectiveness of defoliation, sunscreens and protective nets depended on the meteorological conditions during each growing season.

Total yield, including grapes with different levels of damage, as well as the vigour of vines, were not impacted by the viticultural measures. Malic acid and total acidity concentrations in the must were decreased by early defoliation compared to no defoliation within each year, while must weight was not influenced by any measure. In conclusion, this study compared the potential of different prevention strategies and highlighted a combined positive effect of early defoliation at two experimental sites and within each growing season: Both sunburn necrosis and rot severity were reduced in comparison to the respective maximum extent.

KEYWORDS: climate change, early defoliation, heat wave, rot infestation, shading net, sunscreen, viticultural management strategy

INTRODUCTION

Grapevine (*Vitis vinifera* L.) is cultivated worldwide to produce table grapes, raisins, juice and wine (Keller, 2010). According to a recent estimation, its cultivation area comprises 7,300,000 ha, attributing a non-negligible economic importance in many countries (International Organisation of Vine and Wine, 2021). ‘Riesling’ is among the most planted grape cultivars for wine production in both Germany and Luxembourg, accounting for 23.6 % and 12.8 % of their total viticulture area, respectively (Deutsches Weininstitut GmbH, 2024; Institut Viti-Vinicole, 2024). Its global cultivation comprises 63,936 ha (Deutsches Weininstitut GmbH, 2022). However, besides ‘Bacchus’, ‘Chardonnay’, or ‘Sémillon’, ‘Riesling’ is known to be a sunburn-susceptible, white cultivar (Webb *et al.*, 2010; Calderón-Orellana *et al.*, 2018; Gambetta *et al.*, 2021).

Viticulture is strongly influenced by climatic and meteorological conditions. Consequently, current anthropogenic climate change threatens viticulture in several regions (Santos *et al.*, 2020). Global warming is leading to a substantial increase in frequency, duration and intensity of heat waves (Perkins-Kirkpatrick & Lewis, 2020), and the annual maximum daily air temperature is forecasted to rise (Intergovernmental Panel on Climate Change, 2023). Climate change could increase the likelihood of sunburn events causing severe yield losses and reductions of wine quality in susceptible cultivars (Gambetta *et al.*, 2021; Szmania *et al.*, 2023).

Sunburn is caused by intense solar radiation. Thereby, all spectral components comprising ultraviolet B (UV-B; 280–315 nm), ultraviolet A (UV-A; 315–400 nm), visible (VIS; 400–780 nm) and infrared radiation (IR; ≥ 780 nm) contribute to abiotic damage to fruits (Rabinowitch *et al.*, 1974; Schrader *et al.*, 2003; Hulands *et al.*, 2014; Gambetta *et al.*, 2021). Sunburn symptoms can affect berry skin, pulp and grape rachis (Zschokke, 1931). Similar to apples, two types of symptoms can be distinguished in vineyards: sunburn necrosis and sunburn browning. Sunburn necrosis includes cuticula modification, epidermal as well as subepidermal cell death, accompanied by a yellow-brown to red-violet colouration and often followed by tissue collapse or shrivelling (Zschokke, 1931; Schrader *et al.*, 2001; Gambetta *et al.*, 2021). Intense solar radiation can further degrade carotenoids, leading to the formation of 1,1,6-trimethyl-1,2-dihydronaphthalene (TDN), which is associated with the petrol-like off-flavour in ‘Riesling’ wines (Simpson, 1978; Ziegler *et al.*, 2020; Szmania *et al.*, 2023). Sunburn browning comprises a sublethal damage with

brown spots on berry skins, which can be attributed to the oxidation of polyphenols, resulting in more pronounced oxidised off-flavours in wines (Schrader *et al.*, 2001; Gambetta *et al.*, 2021; Rustioni *et al.*, 2023). Besides differences in sunburn susceptibility between cultivars, the stage of berry development, water status of vines as well as its state of adaptation to elevated air temperatures and radiation intensities play a crucial role in determining the stress at which irreversible cell damage occurs (Tarara & Spayd, 2005; Gambetta *et al.*, 2021; Müller *et al.*, 2023).

In the last decades, defoliation of the bunch zone post-flowering has become a standard and mostly mechanical viticultural tool in many wine-growing regions due to its high potential to mitigate bunch rot (Zoecklein *et al.*, 1992; Diago *et al.*, 2010; Molitor *et al.*, 2011). Numerous positive effects on grape health status can be attributed to an increased canopy aeration and sun exposure, which prevents germination and infection by fungal pathogens, a better application and adhesion of fungicides on berry surfaces (Zoecklein *et al.*, 1992), a less compact grape architecture (Molitor *et al.*, 2011) as well as a hardening effect of berry skins and an increased accumulation of phenolic substances (Fox, 2006). Defoliation at *véraison* is a common practice to increase aroma compounds in white grape berries (Yue *et al.*, 2020) and anthocyanin contents in red cultivars (Hunter *et al.*, 1991). The likelihood to trigger sunburn necrosis is enhanced when defoliation is conducted at this developmental stage in comparison to post-flowering (Gambetta *et al.*, 2022), presumably due to the decrease of chlorophylls and carotenoids as well as the low content of flavonols, anthocyanins and antioxidants in grape berries (Gambetta *et al.*, 2021). However, sunburn susceptibility of ‘Riesling’ grapes can be decreased seven days after defoliation, indicating a rapid adaptation process (Müller *et al.*, 2023).

Since grape berries receive direct solar radiation by defoliation measures, particularly suddenly exposed grapes are highly susceptible to sunburn damage (Gambetta *et al.*, 2021). Application of radiation-reflecting sunscreens such as kaolin [$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$] can mitigate the detrimental effects of heat and radiation in grapevine (Lobos *et al.*, 2015; Dinis *et al.*, 2020). The fruit temperature of kaolin-covered grapes can be decreased by about 1 °C, while light reflectance is enhanced. The concentration of kaolin sprayed onto fruit surfaces, as well as the number of applications conducted post-flowering to *véraison*, are linked to its effectiveness in reducing heat damage (Lobos *et al.*, 2015; Teker, 2023). Kaolin application can reduce sunburn damage on grapes, while yield, organic acid and anthocyanin contents are increased (Frioni *et al.*, 2019). Furthermore, the quality of

‘Riesling’ wines could be improved by the application of kaolin and lime onto grapes, mitigating unpleasant notes caused by sun exposure and retaining fruitiness and sweetness of the wines (Szmania *et al.*, 2023).

Alternatively, protective nets can prevent damage to grapes caused by several environmental impacts such as animals, hail or solar radiation. The purpose of each net depends on colour, mesh size and texture, revealing different shading factors (Castellano *et al.*, 2008). The number of shrivelled berries can be halved when vines are shaded by 23 % which leads to an increased yield (Oliveira *et al.*, 2014). Berry temperature can be decreased by about 3.8 °C when a net with a shading factor of 35 % is used, while no differences in fruit chemical composition are observed (Lobos *et al.*, 2015). However, excessive shading by 70 % imbalances the carbon metabolism when vines are completely covered (Greer *et al.*, 2011).

Further viticultural management strategies against sunburn damage consider reduced row widths and higher canopies to ensure mutual shading (Danenberg, 2019), minimal pruning (Gambetta *et al.*, 2021) and row orientation. Sunburn occurrence can be twice as high in north-south oriented than in east-west oriented vineyards (Webb *et al.*, 2010). The effects of anti-transpirant products on sunburn reduction are inconsistent due to the ambivalent impact of transpiration by cooling and dehydrating of grape berries at the same time (Gambetta *et al.*, 2021). Although evaporative cooling by micro-sprinklers above or below the canopy reduces sunburn and berry dehydration by lowering the fruit surface temperature by almost 12 °C (Greenspan, 2009), its necessity should be carefully considered in regard to drought conditions.

This study aimed to carry out a comprehensive agronomic evaluation of different protective strategies against sunburn necrosis on ‘Riesling’ grapes under various environmental conditions. Field experiments were conducted within three wine-growing regions in Central Europe and across two contrasting seasons to evaluate the effects of the timing of bunch zone defoliation. Investigations were extended at one experimental site to include different sunscreens as well as protective nets. Experiments aimed at gaining insights into the occurrence of sunburn and revealing how to avoid damage by comparing the effectiveness of different measures and their interactions. Furthermore, the study was combined with a crosslinking to rot infestation as well as to the impacts on total yield, must composition and vigour of vines.

MATERIALS AND METHODS

1. Experimental sites and designs

A defoliation experiment was designed to evaluate the effect of the timing of bunch zone defoliation on sunburn occurrence across the three wine-growing regions, Palatinate, Rheingau and Moselle in Central Europe. Experimental vineyards included the individual sites “Mußbacher Johannitergarten” of the “Staatsweingut mit Johannitergut Neustadt” in the district Mußbach of Neustadt an der Weinstraße (NW), Rhineland-Palatinate, Germany; “Eibinger Magdalenenkreuz” of the

“Hochschule Geisenheim University” in Geisenheim (GM), Hesse, Germany; and “Remich Goldberg – Berg IVV” of the “Institut Viti-Vinicole” in Remich (RM), Remich, Luxembourg. Field experiments were conducted within the growing seasons of 2021 and 2022 using *V. vinifera* ‘Riesling’ as a sunburn-sensitive, white cultivar. Besides the defoliation experiment at multiple sites, a sunscreen experiment as well as a protective net experiment were conducted at the site NW to investigate the application of different radiation-reflecting sunscreens and shading by various protective nets (Figure S1). The respective experiments at each site were randomised in block designs. An overview of the different cultivation and experimental conditions at each site is indicated in Table S1.

2. Defoliation experiment

The field experiment consisted of three defoliation approaches, comprising no defoliation (ND), early defoliation (ED) and late defoliation (LD) at each site. Bunch zones were manually completely defoliated on both canopy sides between the end of flowering and fruit set (BBCH stages 69-71; Lorenz *et al.*, 1995) or at bunch closure (BBCH stages 77-79), respectively (Figure S1). For this purpose, exclusively grape-covering leaves were removed. In order to maintain the degree of defoliation, a second defoliation was conducted simultaneously at bunch closure within the ED approach. The exact times of LD were determined according to weather forecasts (www.meteoblue.com) with maximum air temperatures of at least 30 °C and ideally cloudless skies. These conditions were expected to trigger sunburn necrosis, and defoliation measures were carried out beforehand (Table S1). For this experiment, 32 vines each in three field replicates at NW, eight vines each in three field replicates at GM, and eight vines each in four field replicates at RM were considered. Each defoliation approach was compared to ND.

3. Sunscreen experiment

In order to investigate different sunscreens, two radiation-reflecting sunscreens were integrated into the defoliation experiment as further experimental elements at the site NW. Defoliated vines included approaches with and without application onto grapes, whereas ND vines received no application. CutiSan® (Biofa AG, Münsingen, Germany) was tested as a kaolin product in a 5 % suspension and compared to fiMUM®-Fruchtkalk® (Schneider Verblasetechnik e. K., Kleines Wiesental-Wies, Germany) as a lime product in a 2 % suspension for their sunburn-reducing effects (Figure S1). Due to possible damage caused by high pH values, the concentration of lime had to be reduced to 2 %. The respective additives were selected due to the most proper coverage of grapes within a preliminary test (Figure S3 and Table S2). Applications were conducted from pea size (BBCH stage 75) onwards within the ED approaches when the above-mentioned weather conditions were forecasted or immediately following LD at bunch closure (Table S1). Both suspensions were prepared by providing about one-third of the final volume of water to which the respective additives

and sunscreens were added successively. The suspension was homogenised and filled up with water to the final volume. To prevent sedimentation, the suspension was kept in motion until decanting into the tank of the running engine-powered backpack sprayer (STIHL SR 450, ANDREAS STIHL AG & Co. KG, Waiblingen, Germany). The water expense comprised 600 L ha⁻¹. The accelerator was set to one-third of maximum performance, and the flow volume to half of the maximum to obtain a proper coverage and even spray patterns given by a sufficient suspension expense. Applications were conducted at a horizontal angle on both sides of the canopy using a cone grid and in an idle state to prevent spray traces in the neighbouring row. Following visual assessments after precipitation events in 2021, a renewed application within the ED approaches was necessary, which was simultaneously conducted with the application at bunch closure (Table S1). Similar to the defoliation experiment, 32 vines each in three field replicates were considered. Each sunscreen was compared to the respective ED or LD approach without sunscreen.

4. Protective net experiment

Three types of protective nets (P.R.P. Produzione Reti Plastiche Srl., Ostuni, Italy; distributed by Whailex, WAGNER GmbH, Ehrenkirchen-Kirchhofen, Germany) intended to shield grapes from hail (AG RG 26/3), solar radiation (GI RO 080) or the spotted wing *Drosophila* (SWD, *Drosophila suzukii* Matsumura; GI RO 101) differing in colour, mesh size and shading factor were installed and investigated within a separate experiment at the site NW (Figure S1 and Table S3). Whole vines were vertically shaded on both canopy sides from pre-flowering onwards throughout each growing season, and LD was conducted prior to the above-mentioned weather conditions, respectively (Figure S4 and Table S1). For this experiment, 20 vines each in three field replicates were considered. Each protective net was compared to the LD approach without a protective net.

5. Field assessments, laboratory analyses, and data evaluations

Meteorological conditions were measured throughout the growing seasons by meteorological stations close to the experimental sites within 5 min at NW, 15 min at GM and daily intervals at RM above 2 m height, respectively. Furthermore, phenology was recorded at each site. Microclimatic conditions were measured by HOBO® U23-002 Pro v2 External Temp/RH Data Logger with Solar Radiation Shield RS3-B (Onset Computer Corp., Bourne, Massachusetts, USA) within 15 min intervals installed inside the bunch zones of each field replicate at NW. Midday stem water potential was measured at NW in 2022, three days after *véraison* on three ND vines within each experiment with six full-grown leaves using the Scholander pressure chamber M 615 (MMM tech support GmbH & Co. KG, Berlin, Germany). Leaves were equilibrated with an aluminium bag for 20 min, and measurements were conducted within 30 s after petiole cutting (Scholander *et al.*, 1965; Levin, 2019).

Sunburn necrosis of each approach within the experiments was visually assessed between a maximum of 9 days before and 14 days after *véraison* when the above-mentioned weather conditions were no longer forecasted at the respective sites. At least 60 full-grown grapes of each field replicate taken from healthy vines outside of marginal areas were equally selected from each side of the canopy, turned and assessed using a severity scale with increments of five percent. Maximum 12 days before harvest, each approach within the experiments was further visually assessed for rot infestation at each site comprising grey mould (*Botrytis cinerea* Pers. Fr.), blue mould (*Penicillium* spec. Link) and sour rot (acetic acid bacteria and wild yeasts) using at least 30 grapes of each field replicate (Table S1). The procedure of rot infestation assessments was the same as that of sunburn necrosis assessments.

Total yield, including grapes with different levels of damage and pruning wood of at least ten vines of each field replicate within the approaches at NW, were weighed, whereas total yield was calculated for one hectare and pruning wood for one vine (Table S1). Furthermore, samples of 100 berries of each field replicate within the approaches were weighed at harvest, and their musts were analysed by Fourier-transform infrared (FTIR) spectroscopy using WineScan™ Auto with the GrapeScan™ calibration (FOSS A/S, Hillerød, Denmark) at NW. For this purpose, berry samples were homogenised into must using the BagMixer® 400 CC® (INTERSCIENCE S.A.R.L., Saint-Nom-la-Bretèche, France) with a speed of 10 strokes s⁻¹ for 30 s.

To determine the reflectance of kaolin and lime, each sunscreen was sprayed as a suspension with the respective additives (Table S2) onto a WANTOUTH aluminium plate (15 cm × 15 cm × 0.5 mm; Aixin Datong Technology, Guangdong Sheng, China) using an airbrush with less than 70 kPa. The reflectance was measured at the Chemistry Research Institute of the University of La Rioja at least six times to address homogeneity across the sample surfaces. The setup used was composed of a DH-2000-BAL light source connected through a 600 µm optic fibre to an ISP-50-8-R-GT integrating sphere collecting direct as well as scattered reflectance, and was attached to the HDX00944 spectrometer with a 1,000 µm optic fibre (Ocean Optics B.V., EW Duiven, The Netherlands). For registering the spectra, 20 scans were averaged with an integration time of 4 s, using nonlinearity correction and a boxcar width of 5. The shading factors of the investigated protective nets (Table S3) were calculated based on four horizontal measurements at the highest sun position on cloudless days in June and August using the CCD Array Spectrometer BRC112E-U (B&W Tek Inc., Newark, New Jersey, USA) at NW. Spectral measurements were averaged with an integration time of 100 ms for 100 times in June and 250 ms for 5 times in August, adjusted due to the respective spectrum saturations. Reflectance and shading measurements were conducted within the wavelength range of 280–810 nm and 280–850 nm, respectively.

Data from each experiment were site-wise, year-wise and combined analysed using IBM SPSS Statistics (version: 29.0.0.0 (241); IBM Corp., Armonk, New York, USA).

Firstly, each data set was evaluated for normal distribution by the Shapiro-Wilk test as well as for homogeneity of variance by the Levene test. Data were transformed by natural logarithm, square, square root or reciprocal as far as normal distribution or homogeneity of variance was not obtained. The subsequent statistical analyses were conducted using a linear model with *t*-tests or multifactorial ANOVA for the individual factors site, year, defoliation, sunscreen and protective net or combinations of measures at a significance level of $\alpha = 0.05$, respectively. LSD or Tukey-HSD were used as post-hoc tests for year-wise or complete data sets, respectively. The non-parametric Mann-Whitney-U test or Kruskal-Wallis test was used if no normal distribution or homogeneity of variance could be obtained.

RESULTS

1. Meteorological conditions and phenology

The two growing seasons were contrasting regarding weather conditions at each experimental site. While in 2021, the maximum air temperature since LD was lower and precipitation rates between June and August were higher, the subsequent year was characterised by hotter and drier conditions. Maximum air temperatures were 31.1 ± 0.7 °C in 2021 as well as 38.7 ± 0.1 °C in 2022 across the sites and were achieved after LD, respectively. In 2022, the number of hot days with a minimum of 30 °C air temperature recorded from LD onwards increased by at least 28 days when compared to the previous year. The maximum ambient temperature within the LD bunch zones at NW was 1.0 ± 0.2 °C higher in comparison to the measurements at 2 m height across both years. Measurements of sunshine duration, solar radiation intensity, wind speed, and relative humidity on the respective hottest day since LD, did not reveal noticeable differences between the experimental sites. In 2022, precipitation rates between June and August decreased by 144.5 ± 49.0 mm across the sites when compared to 2021 (Table S5). Midday stem water potential of ND vines across the experiments measured in 2022 at NW was -1.0 ± 0.0 MPa (Table S6), and grapes were partially or completely affected by sunburn necrosis (Figure S2). Regarding the hottest day since LD of each growing season, grapes were at the phenological stage of bunch closure at each experimental site. The onset of *véraison* (BBCH stage 81) showed a developmental delay of 13 ± 1 days in 2021 across the sites when compared to 2022 (Table S5).

2. Defoliation

The experimental sites were compared by defoliation measures, leading to a varying extent of sunburn necrosis. In descending order, the highest sunburn severity, with 17.2 ± 0.5 % of berries affected, was recorded at RM in 2021, followed by 11.4 ± 1.5 % at NW in 2022 and 2.9 ± 0.5 % at GM in 2021 within the respective LD. The extent of damage was among the lowest at GM and among the highest at RM within each growing season (Figure 1 and Table S8).

ED showed a reduction of sunburn necrosis when compared to LD within each growing season at NW and RM. The positive impact of ED was further confirmed across both experimental years for both sites. At GM, ED led exclusively in 2021 to a lower extent of sunburn necrosis compared to LD. When ND was conducted, sunburn damage was consistently reduced in comparison to LD during each and across both growing seasons at NW. However, ND at RM showed exclusively in 2021 less damage than LD, when the overall levels of sunburn necrosis were increased in comparison to 2022 (Figure 1 and Table S8).

The defoliation measures conducted at each experimental site were additionally assessed in terms of their impact on rot infestation. In 2021, rot severity was higher than in the subsequent year at each site. In descending order, maximum infestation was 35.4 ± 1.4 % at GM, followed by 13.5 ± 3.0 % at NW and 9.1 ± 1.7 % at RM. Rot severities were among the lowest at RM within each experimental year (Figure 2 and Table S8).

Both defoliation approaches, ED and LD, revealed a positive impact on preventing rot infestation within each and across both growing seasons at NW when compared to ND, respectively. At RM, rot severity was exclusively reduced by ED in comparison to ND within each and across both experimental years, respectively (Figure 2 and Table S8).

3. Sunscreens

The applications of kaolin and lime onto grapes were compared in terms of their preventive effects against sunburn necrosis within the respective ED and LD approaches at NW in each experimental year. Kaolin, considered as a factor within both defoliated approaches, was able to reduce sunburn necrosis in 2021 in comparison to the defoliated approaches without sunscreen. However, no impact of kaolin was recorded when comparing the respective ED and LD approaches separately in any year. In contrast, lime could reduce sunburn damage within the LD approach in each growing season, as well as within the ED approach in 2021. Thus, combining ED and application of lime provided two consecutive protective effects in 2021 when compared to the LD approach without sunscreen. The overall extent of sunburn necrosis was higher in 2022 than in 2021 (Figure 3 and Table S8).

In order to link sunburn assessments with product specifications, the reflectance of each sunscreen was measured on aluminium plates. On average, kaolin showed a slightly higher reflectance along the investigated spectrum than lime, revealing a total reflectance of 62 ± 2 % and 54 ± 5 %, respectively (Table S4). The appearance of grapes covered by the sunscreens also differed, displaying a metal-like glossy coverage with kaolin and a duller coverage with lime (Figure S3). No differences among defoliation and application measures were recorded in the maximum ambient temperatures within the bunch zones on the respective hottest day since LD of each year (Table S7).

Regarding rot infestation, application of sunscreens did not show an additional prevention beyond the impact of defoliation measures (Figure 4 and Table S8).

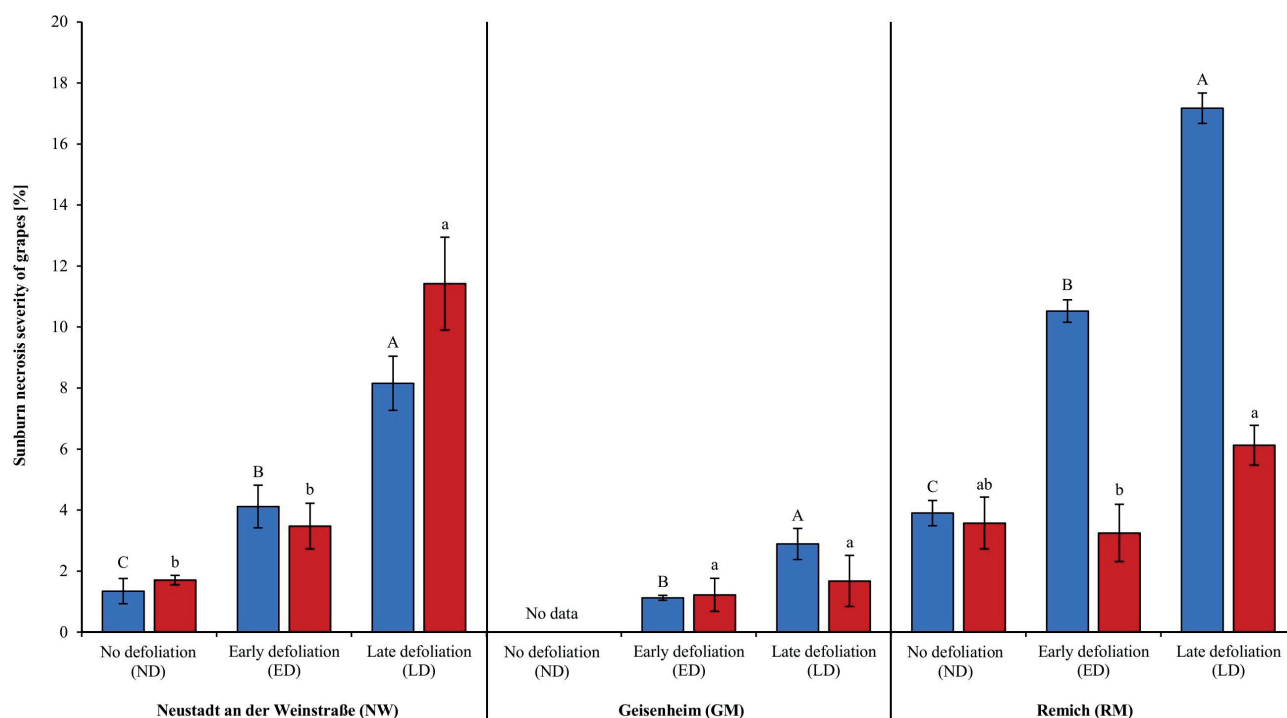


FIGURE 1. Sunburn necrosis severity of grapes within the defoliation experiment in the growing seasons 2021 (blue bars) and 2022 (red bars).

Bars show mean values of at least three field replicates comprising a minimum of 60 grapes each, with error bars indicating the respective standard errors. Data were site-wise and year-wise statistically analysed using ANOVA with LSD post-hoc tests. Different upper-case or lower-case letters within each experimental site indicate significant differences between viticultural measures in each year at a significance level of $\alpha = 0.05$, respectively.

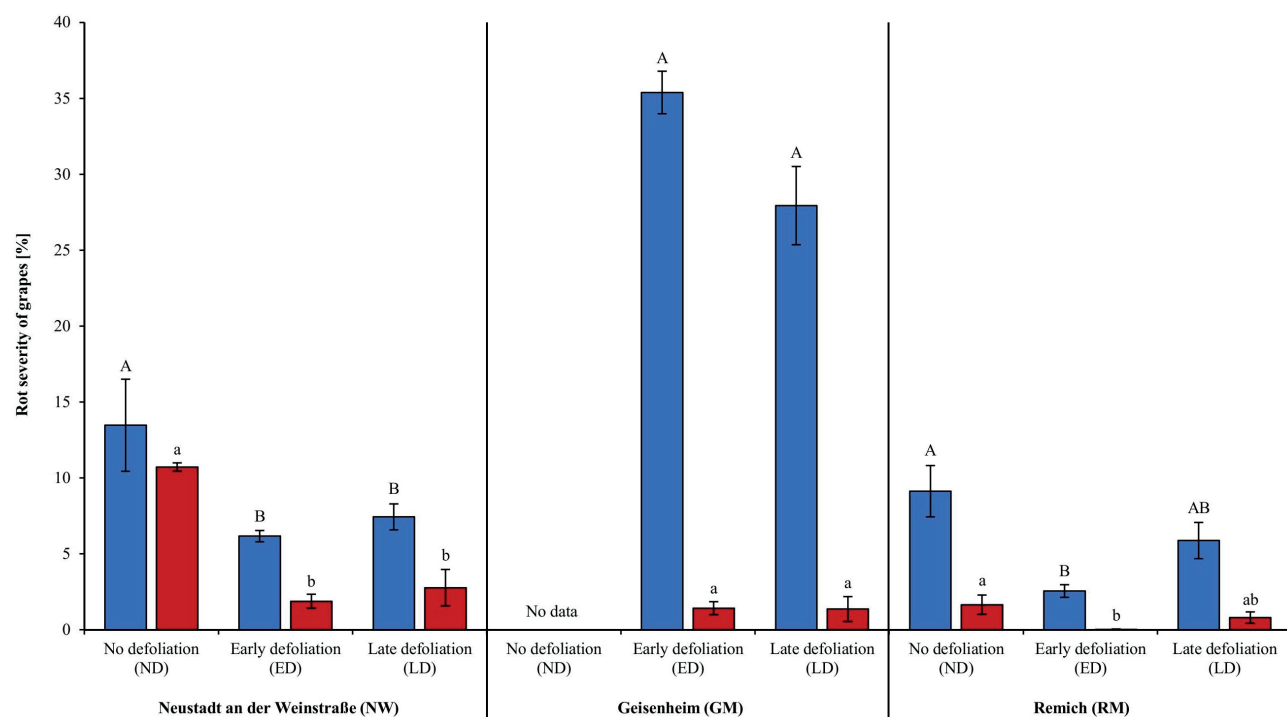


FIGURE 2. Rot severity of grapes within the defoliation experiment in the growing seasons 2021 (blue bars) and 2022 (red bars).

Bars show mean values of at least three field replicates comprising a minimum of 30 grapes each, with error bars indicating the respective standard errors. Data were site-wise and year-wise statistically analysed using ANOVA with LSD post-hoc tests. Data from Remich (RM) in 2022 were previously transformed by the square root. Different upper-case or lower-case letters within each experimental site indicate significant differences between viticultural measures in each year at a significance level of $\alpha = 0.05$, respectively.

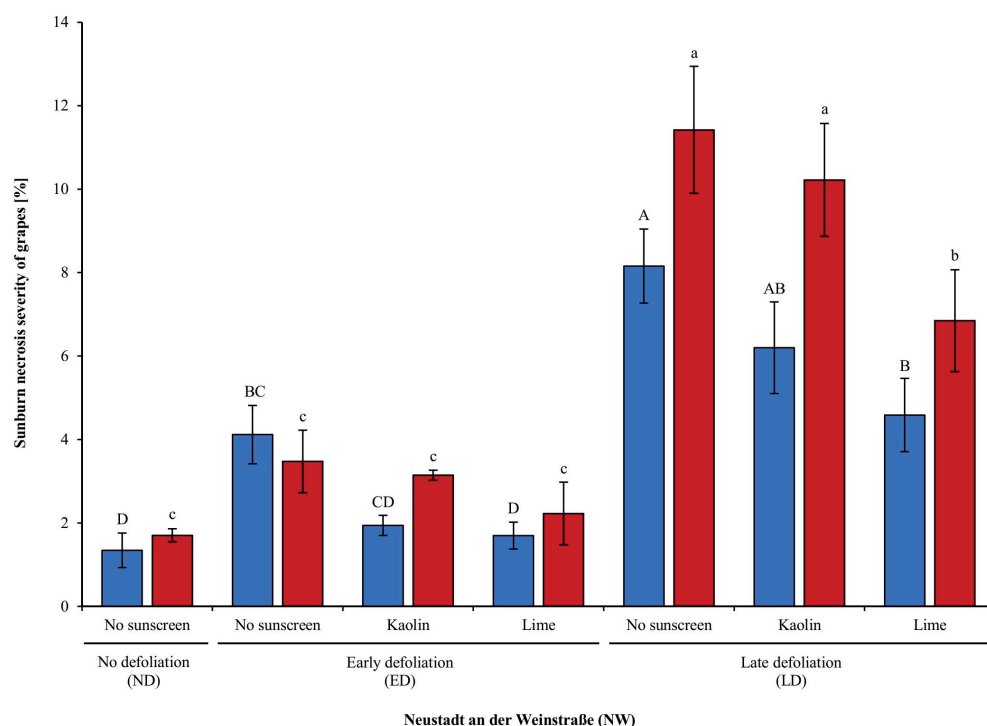


FIGURE 3. Sunburn necrosis severity of grapes within the sunscreen experiment in the growing seasons 2021 (blue bars) and 2022 (red bars).

Bars show mean values of three field replicates comprising 100 grapes each, with error bars indicating the respective standard errors. Data of ND as well as of the ED and LD approaches without sunscreen refer to the defoliation experiment. Data were year-wise statistically analysed using ANOVA with LSD post-hoc tests. Different upper-case or lower-case letters indicate significant differences between viticultural measures in each year at a significance level of $\alpha = 0.05$, respectively.

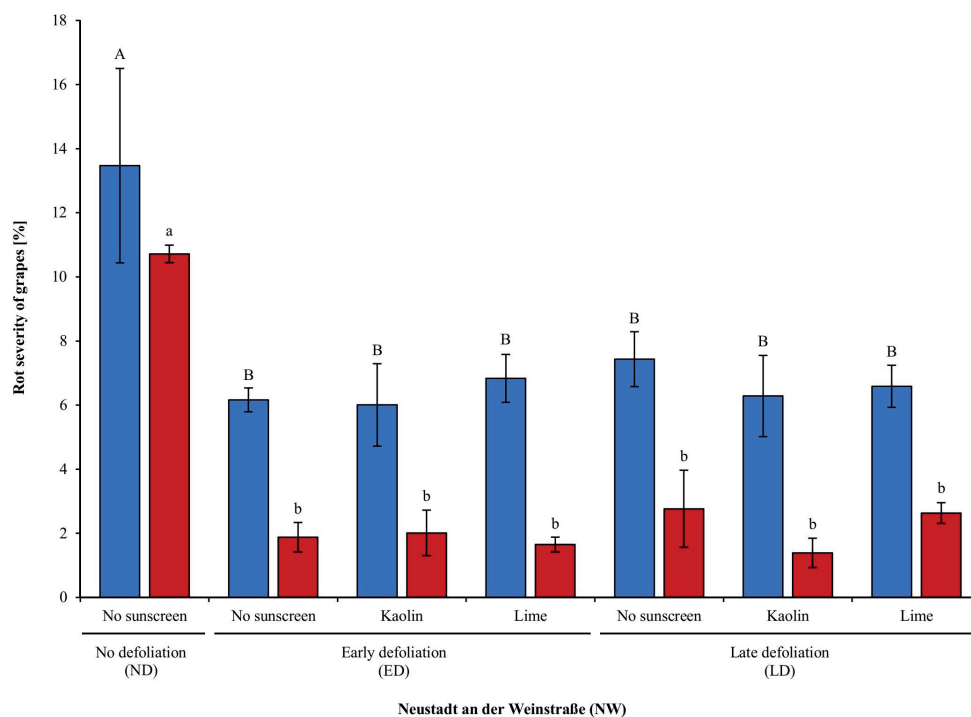


FIGURE 4. Rot severity of grapes within the sunscreen experiment in the growing seasons 2021 (blue bars) and 2022 (red bars).

Bars show mean values of three field replicates comprising 100 grapes each, with error bars indicating the respective standard errors. Data of ND as well as of the ED and LD approaches without sunscreen refer to the defoliation experiment. Data were year-wise statistically analysed using ANOVA with LSD post-hoc tests. Different upper-case or lower-case letters indicate significant differences between viticultural measures in each year at a significance level of $\alpha = 0.05$, respectively.

4. Protective nets

Three types of protective nets within the LD approach were investigated at NW during both growing seasons for their reducing effects on sunburn necrosis. Each of the protective nets was able to lower the damage within each year. However, the respective maximum extent of sunburn necrosis within this experiment was relatively low, comprising 4.5 ± 0.4 % in 2021 as well as 7.1 ± 2.1 % in 2022 (Figure 5 and Table S8).

The shading factor of each protective net was determined by spectral measurements and confirmed the indication provided by the manufacturer. Light transmittance was reduced by 18 ± 1 % with the hail net, 26 ± 4 % with the *D. sukuzii* net and 30 ± 3 % with the shading net (Tables S3 and S4). Consistently, the shading factors along the investigated spectrum were among the lowest with the hail net and among the highest with the shading net. While IR, VIS and UV-A radiation were filtered comparably to the total shading factor of the respective protective net, shielding of UV-B radiation was almost absent, with less than 5 % (Table S4). No differences among the shading measures could be recorded in the maximum ambient temperatures within the bunch zones on the respective hottest day since the LD of each year (Table S7).

Rot infestation was not reduced by any of the protective nets in addition to the defoliation measures (Figure 6 and Table S8).

5. Effectiveness of viticultural measures

The effectiveness against sunburn necrosis varied between experimental sites, growing seasons, defoliation measures, applications of sunscreens, as well as shading by protective nets (Tables 1 and S8). In contrast, the effectiveness against rot infestation was merely dependent on the site, year and timing of defoliation (Figure 2 and Table S8).

ED revealed a positive impact against sunburn severity by 42.8 ± 7.3 % at RM and 59.6 ± 6.6 % at NW across both experimental years when compared to LD, respectively. At both sites, ED was on average more effective in 2022 than in 2021. In contrast, ED showed an effectiveness of 61.1 ± 2.8 % at GM in 2021, but had no influence in 2022 when the overall extent of sunburn damage was the lowest. ND prevented sunburn necrosis exclusively in 2021 at RM by 77.3 ± 2.4 %, but across both growing seasons at NW by 84.3 ± 2.4 % in comparison to the respective LD approaches. In 2022, no differences in terms of sunburn necrosis between ED and ND were observed at NW and RM,

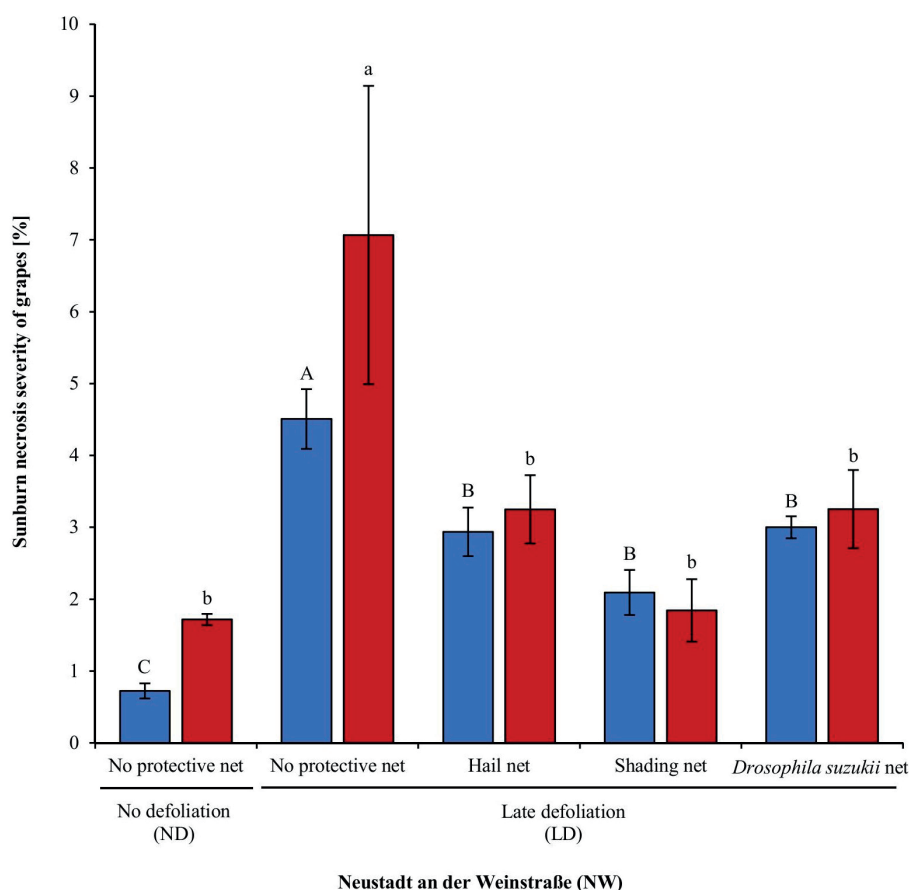


FIGURE 5. Sunburn necrosis severity of grapes within the protective net experiment in the growing seasons 2021 (blue bars) and 2022 (red bars).

Bars show mean values of three field replicates comprising 100 grapes each, with error bars indicating the respective standard errors. Data were year-wise statistically analysed using ANOVA with LSD post-hoc tests. Data from 2022 were previously transformed by natural logarithm. Different upper-case or lower-case letters indicate significant differences between viticultural measures in each year at a significance level of $\alpha = 0.05$, respectively.

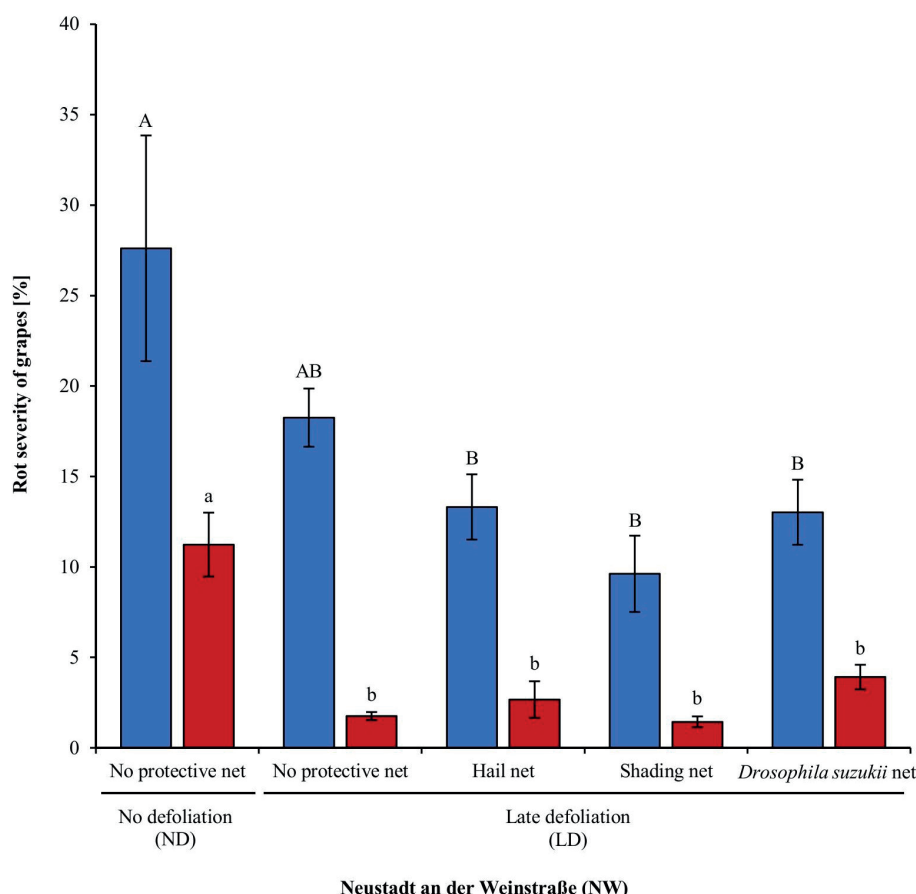


FIGURE 6. Rot severity of grapes within the protective net experiment in the growing seasons 2021 (blue bars) and 2022 (red bars).

Bars show mean values of three field replicates comprising 100 grapes each, with error bars indicating the respective standard errors. Data were year-wise statistically analysed using ANOVA with LSD post-hoc tests. Different upper-case or lower-case letters indicate significant differences between viticultural measures in each year at a significance level of $\alpha = 0.05$, respectively.

respectively (Figure 1; Tables 1 and S8). Both defoliation approaches prevented rot infestation at NW when compared to ND, comprising an effectiveness of LD by 59.5 ± 8.7 % and of ED by 68.4 ± 6.7 % across both growing seasons, respectively. ED was on average even more effective in reducing rot severity at RM, with 85.3 ± 5.5 % in comparison to ND across both years. The mean effectiveness of defoliation measures was higher in 2022 than in 2021 at both experimental sites (Figure 2 and Table S8).

Lime revealed an effectiveness against sunburn damage within the LD approaches at NW by 41.9 ± 6.8 % across both experimental years, while kaolin did not show an impact. Combining ED and application of lime decreased sunburn necrosis by 79.2 ± 3.9 % in 2021. Furthermore, the combination of ED and the respective application of kaolin and lime lowered the extent of sunburn necrosis to the level of ND in 2021 (Figure 3; Tables 1 and S8).

During each experimental year, the protective nets reduced sunburn necrosis at NW, but their mean effectiveness was higher in 2022 when compared to 2021. Sunburn was prevented across both growing seasons by 43.7 ± 5.9 % with the *D. suzukii* net, 44.4 ± 6.2 % with the hail net and 63.7 ± 6.2 % with the shading net, revealing the highest

effectiveness of the shading net. Additionally, the extent of sunburn necrosis within the combinations of LD and any protective net was decreased to the level of ND in 2022 (Figure 5; Tables 1 and S8).

6. Total yield, must composition and vigour of vines

The impacts of viticultural measures on the quantity and quality of grapes and vines were investigated at NW. Total yield comprised 14.9 ± 0.4 t ha⁻¹ in 2021 and 11.7 ± 0.3 t ha⁻¹ in 2022, revealing an increase in both total yield and berry weight in 2021 compared to the subsequent year. Neither defoliation, sunscreen application, nor shading measures had a quantitative impact on total yield, including grapes with different levels of damage, as well as on berry weight within each growing season, respectively (Tables S9 and S10). However, the shading net showed, on average, a reduction of total yield in 2022 (Table S9).

Must analyses using FTIR spectroscopy revealed that variances in must weight and tartaric acid contents within the growing seasons cannot be attributed to any viticultural measure. Malic acid concentration was lower within the ED and LD approaches compared to ND in each and across both

TABLE 1. Effectiveness of viticultural measures against sunburn necrosis during the growing seasons at the experimental sites.

Viticultural measure	Experimental site	Effectiveness against sunburn necrosis in comparison to late defoliation (LD) (%)		
		2021	2022	2021 + 2022
No defoliation (ND)	Neustadt an der Weinstraße (NW)	83.5 ± 5.1	85.1 ± 1.4	84.3 ± 2.4
	Geisenheim (GM)	No data	No data	No data
	Remich (RM)	77.3 ± 2.4	-	-
Early defoliation (ED)	Neustadt an der Weinstraße (NW)	49.5 ± 8.6	69.6 ± 6.6	59.6 ± 6.6
	Geisenheim (GM)	61.1 ± 2.8	-	-
	Remich (RM)	38.7 ± 2.1	46.9 ± 15.3	42.8 ± 7.3
Kaolin*	Neustadt an der Weinstraße (NW)	-	-	-
		-	-	-
Lime*	Neustadt an der Weinstraße (NW)	43.8 ± 10.8	40.1 ± 10.7	41.9 ± 6.8
		79.2 ± 3.9	-	-
Hail net	Neustadt an der Weinstraße (NW)	34.8 ± 7.5	54.0 ± 6.7	44.4 ± 6.2
Shading net	Neustadt an der Weinstraße (NW)	53.6 ± 6.9	73.9 ± 6.1	63.7 ± 6.2
<i>Drosophila suzukii</i> net	Neustadt an der Weinstraße (NW)	33.4 ± 3.4	54.0 ± 7.7	43.7 ± 5.9

The effectiveness of viticultural measures was calculated in comparison to the respective late defoliation (LD) if differences were significant, exclusively. Additionally, sunscreens (*) indicate the effectiveness of the combination of early defoliation (ED) and sunscreen application in the respective second line. Data show mean values of at least three field replicates comprising a minimum of 60 grapes each, with the respective standard errors.

experimental years of the sunscreen experiment. Furthermore, the content of total acidity was decreased within the ED approaches in comparison to ND in each and across both growing seasons. The levels of malic acid and total acidity were higher with the shading net within the LD approach in 2021. Considering lime as a factor within both defoliated approaches revealed an increased pH value in comparison to the defoliated approaches without sunscreen in each and across both growing seasons. Furthermore, the pH value was higher with the shading net in 2021 and with the *D. suzukii* net in 2022 within the LD approaches, respectively. Increases in malic acid and total acidity, as well as a lower pH value, were recorded in 2021 when compared to 2022 (Table 2).

Pruning wood weights were 721.0 ± 22.7 g vine⁻¹ in 2021 and 548.0 ± 18.4 g vine⁻¹ in 2022, revealing a stronger growth in 2021 than in the subsequent year. Defoliation, application and shading measures did not impact the vigour of the vines in each growing season. However, hail net and shading net showed, on average, the lowest vigour in 2022 (Table S11).

DISCUSSION

1. The severity of damage is site-specific and seasonal

Sunburn on grapes is caused by extreme berry temperatures and light exposure, but can be modified in its extent by further stress factors or adaptation status (Smart & Sinclair, 1976; Tarara & Spayd, 2005; Gambetta *et al.*, 2021;

Müller *et al.*, 2023). The highest severities of sunburn necrosis within the defoliation experiment ranged from 2.9 % at GM in 2021 across 11.4 % at NW in 2022 up to 17.2 % at RM in 2021 within LD, representing a different extent between the experimental sites and years. Particularly, the level of sunburn necrosis was lowest at GM across both growing seasons, when compared to NW and RM, respectively (Figure 1 and Table S8). Row orientations in north-south direction, such as at GM and RM, are known to exhibit an increase of sunburn necrosis (Webb *et al.*, 2010; Gambetta *et al.*, 2021; Strack & Stoll, 2021), but seem to have a minor impact in this study. The site-specific differences in the occurrence of damage cannot be related to the exact meteorological conditions or the phenological stage of grapes on the respective hottest day since LD (Figure 1 and Table S5). Whether the age of the vines, the genetics of ‘Riesling’ clones, rootstocks or their interactions (Table S1) could have had an impact on sunburn susceptibility needs to be further investigated.

Both experimental years varied in terms of duration and intensity of heat waves since LD at each site. In 2022, maximum air temperature was increased for a longer period of time in comparison to 2021 (Table S5), and according to Deloire and Rogiers (2014), the measured midday stem water potential indicated a moderate drought stress of the vines at NW (Table S6). Drought stress is known to lead to a higher canopy porosity by reduced shading foliage, which enhances sun exposure of grapes and increases sunburn necrosis (Tarara & Spayd, 2005).

TABLE 2. Must compositions of viticultural measures at the site Neustadt an der Weinstraße (NW).

Experiment	Defoliation	Sunscreen or protective net	Must weight [°Oe]		Malic acid [g L ⁻¹]		Tartaric acid [g L ⁻¹]		Total acidity [g L ⁻¹]		pH value	
			2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Sunscreen experiment	No defoliation (ND)	No sunscreen	82.7 ± 1.5 (A)	82.0 ± 0.6 (ab)	5.9 ± 0.1 (A)	4.8 ± 0.5 (a)	6.8 ± 0.0 (B)	7.4 ± 0.2 (a)	10.6 ± 0.2 (A)	8.8 ± 0.5 (a)	3.10 ± 0.03 (AB)	3.30 ± 0.00 (a)
			83.0 ± 1.7 (A)	82.3 ± 1.5 (ab)	4.4 ± 0.2 (C)	2.7 ± 0.2 (b)	7.4 ± 0.3 (A)	6.6 ± 0.2 (b)	9.7 ± 0.1 (CD)	6.3 ± 0.2 (bc)	3.06 ± 0.01 (BC)	3.18 ± 0.04 (b)
	Early defoliation (ED)	Kaolin	82.7 ± 1.5 (A)	83.7 ± 1.2 (a)	4.5 ± 0.2 (C)	2.7 ± 0.1 (b)	7.4 ± 0.2 (A)	6.0 ± 0.2 (d)	9.8 ± 0.1 (BCD)	5.8 ± 0.1 (c)	3.04 ± 0.02 (BC)	3.22 ± 0.01 (ab)
			84.7 ± 1.2 (A)	83.7 ± 1.3 (a)	4.4 ± 0.0 (C)	2.7 ± 0.1 (b)	7.1 ± 0.1 (AB)	6.1 ± 0.1 (cd)	9.2 ± 0.1 (D)	5.8 ± 0.1 (c)	3.14 ± 0.01 (A)	3.24 ± 0.01 (ab)
	Late defoliation (LD)	No sunscreen	80.0 ± 4.0 (A)	79.3 ± 1.7 (b)	4.9 ± 0.1 (BC)	3.0 ± 0.3 (b)	7.5 ± 0.0 (A)	6.5 ± 0.2 (bc)	10.2 ± 0.2 (ABC)	6.6 ± 0.1 (b)	3.06 ± 0.03 (BC)	3.19 ± 0.03 (b)
			79.0 ± 2.9 (A)	79.7 ± 0.9 (b)	5.2 ± 0.3 (B)	2.9 ± 0.2 (b)	7.3 ± 0.2 (AB)	6.6 ± 0.2 (b)	10.4 ± 0.4 (AB)	6.4 ± 0.1 (bc)	3.03 ± 0.03 (C)	3.21 ± 0.04 (b)
		Lime	81.7 ± 0.9 (A)	80.3 ± 1.2 (ab)	4.9 ± 0.1 (BC)	2.9 ± 0.1 (b)	7.1 ± 0.2 (AB)	6.3 ± 0.1 (bcd)	9.8 ± 0.2 (BCD)	6.2 ± 0.1 (bc)	3.10 ± 0.01 (AB)	3.25 ± 0.02 (ab)
			82.9 ± 0.7 (A)	77.5 ± 1.7 (a)	5.2 ± 0.1 (A)	2.7 ± 0.1 (a)	6.9 ± 0.1 (A)	7.0 ± 0.2 (a)	10.1 ± 0.1 (A)	6.9 ± 0.2 (a)	2.98 ± 0.02 (B)	3.09 ± 0.01 (ab)
		No protective net	79.4 ± 0.4 (A)	76.1 ± 0.8 (a)	4.2 ± 0.2 (B)	2.4 ± 0.1 (ab)	6.6 ± 0.1 (A)	7.0 ± 0.1 (a)	8.8 ± 0.1 (B)	6.6 ± 0.1 (ab)	2.99 ± 0.02 (B)	3.08 ± 0.02 (b)
			80.3 ± 1.4 (A)	77.7 ± 1.5 (a)	4.8 ± 0.1 (AB)	2.3 ± 0.1 (b)	6.5 ± 0.2 (A)	6.9 ± 0.2 (a)	9.4 ± 0.3 (AB)	6.3 ± 0.1 (b)	2.99 ± 0.03 (B)	3.13 ± 0.02 (ab)
Protective net experiment	Late defoliation (LD)	Shading net	79.1 ± 2.9 (A)	79.4 ± 0.7 (a)	5.2 ± 0.4 (A)	2.4 ± 0.1 (ab)	7.2 ± 0.2 (A)	6.9 ± 0.0 (a)	10.1 ± 0.2 (A)	6.4 ± 0.1 (b)	3.11 ± 0.03 (A)	3.13 ± 0.02 (ab)
			78.5 ± 0.6 (A)	76.3 ± 1.0 (a)	4.9 ± 0.1 (A)	2.4 ± 0.1 (ab)	6.5 ± 0.6 (A)	6.8 ± 0.1 (a)	9.6 ± 0.4 (AB)	6.4 ± 0.1 (b)	2.97 ± 0.03 (B)	3.14 ± 0.02 (a)

Data show mean values of three field replicates comprising 100 berries each, with the respective standard errors. Statistical analyses were conducted for each experiment, measurement and growing season using ANOVA with LSD post-hoc tests. Data from the must weight in 2021 within the sunscreen experiment were previously square-transformed. Different uppercase or lower case letters in the brackets within each experiment and measurement indicate significant differences between viticultural measures in each year at a significance level of $\alpha = 0.05$, respectively.

However, the level of sunburn necrosis at RM was unexpectedly higher in 2021, despite the lowest maximum air temperature since LD and the highest precipitation rates (Figure 1; Tables S5 and S8). By contrast, Gambetta *et al.* (2022) examined two vineyards within one growing season and observed less sunburn damage in the vineyard at a higher altitude, accompanied by lower ambient temperatures. Berry temperature is determined by the combination of air temperature and light exposure (Smart & Sinclair, 1976), which is why direct solar radiation might have contributed more intensely to sunburn necrosis on grapes than merely air temperature on the hottest day in 2021 at RM. The interplay of meteorological conditions and physiological responses seems to be highly site-specific and temporally variable, which complicates the identification of causes for sunburn necrosis and its prediction.

Regarding rot severity, differences between experimental sites and years might be linked to the humidity during the maturation time, since precipitation rates during each growing season were not related to the respective damage (Figure 2; Tables S5 and S8).

2. Early defoliation reduces sunburn necrosis and rot infestation

Even though ND prevented sunburn damage on average the most compared to LD across both growing seasons at NW (Figure 1 and Table S8), defoliation of the bunch zone post-flowering and at *véraison* has become widespread viticultural practice, because of phytosanitary advantages and positive effects on grape quality (Zoecklein *et al.*, 1992; Molitor *et al.*, 2011; Yue *et al.*, 2020). However, levels of sunburn necrosis are potentially higher when defoliation is conducted at *véraison* than post-flowering (Gambetta *et al.*, 2022). Simultaneous experiments at three sites and across two contrasting growing seasons highlighted the preventive impact against sunburn necrosis by ED between the end of flowering and fruit set in comparison to LD at bunch closure (Figure 1 and Table S8). Defoliation around flowering induces adaptation processes in grapes such as an increase in thickness of berry skins and higher polyphenol contents, but furthermore provokes less compact grape architectures, which all can lead to sunburn tolerance (Smart & Sinclair, 1976; Molitor *et al.*, 2011; Pastore *et al.*, 2013; Verdenal *et al.*, 2019; Gambetta *et al.*, 2022).

Defoliation represented an effective measure against rot severity at NW within each growing season in comparison to ND, whereas exclusively ED revealed a positive impact at RM when compared to ND during each experimental year (Figure 2 and Table S8). Defoliation post-flowering or at *véraison* has been shown to lead to lower rot infestation (Ferrari *et al.*, 2017), improving aeration of the bunch zone, favouring grape exposure to sun and wind, as well as enhancing drying of wet grapes after precipitations (Zoecklein *et al.*, 1992; Molitor *et al.*, 2011). Furthermore, sun-exposed berries or less compact grapes develop a thicker cuticle layer than shaded berries or compact grapes, which can diminish *B. cinerea* infections (Rosenquist & Morrison, 1989).

3. Protection by sunscreens against sunburn necrosis is product-specific

Radiation-reflecting sunscreens can be applied on sun-exposed grapes as a short-term reaction prior to forecasted heat waves to reduce the extent of sunburn damage. Particularly, kaolin is known for its sunburn-preventing properties when sprayed onto grapes (Lobos *et al.*, 2015; Teker, 2023). However, comparing the application of kaolin and lime onto grapes at NW in terms of sunburn reduction revealed that lime was able to reduce the damage effectively, despite the lower concentration used (Figure 3; Tables S2 and S8). The effectiveness of kaolin seems to depend on the product applied, since Nufresh® and Surround® WP were able to reduce sunburn necrosis (Lobos *et al.*, 2015; Teker, 2023), while CutiSan® was not. Within the LD approach, lime decreased the damage during each growing season. Lower maximum air temperatures since LD in 2021 compared to 2022 might have favoured an additional effectiveness of lime within the ED approach. Due to the precipitations in 2021, a minor residual coverage and the renewed application within the ED approach might have further led to a more intensive coverage of lime on the grapes and thus, contributed to the effectiveness beyond the impact of ED (Figure 3; Tables S1, S5 and S8). Since the additives differed in the respective suspension of kaolin and lime (Table S2) to ensure a proper coverage on grapes (Figure S3), the combination of the respective components might also have influenced the effectiveness against sunburn necrosis.

The reflectance of UV and IR radiation by kaolin is determined by its heat-processed properties and the amounts applied (Glenn *et al.*, 2002; Glenn & Puterka, 2005). Since reflectance measurements were not related to the effectiveness of sunburn mitigation (Figure 3; Tables S4 and S8), reflectance of IR radiation beyond the measured spectrum might be of greater importance. However, differences between the adhesion of sunscreens on the surfaces of aluminium plates and berry cuticula have to be considered as well.

Beyond the effect of defoliation, sunscreens did not reduce rot infestation (Figure 4 and Table S8). Ferrari *et al.* (2017) reported the potential of kaolin to lower the severity of *B. cinerea* on grapes, although the impact was not consistent among approaches and vintages.

4. Different protective nets decrease sunburn necrosis

Protective nets represent a long-term and more expensive investment regarding additional installation and maintenance costs, which have to be decided on the basis of the size and economic situation of the individual winery, as well as on further protection benefits. Despite the differences in colour, mesh size and shading factor (Table S3), each of the protective nets at NW reduced sunburn necrosis within the LD approach during each growing season, although the overall extent of damage within this experiment was low (Figure 5). White and black nets with shading factors ranging from 23 % to 35 % have been shown to decrease the level of sunburn damage effectively (Oliveira *et al.*, 2014; Lobos *et al.*, 2015).

The shading factors of each protective net from the UV-A spectral range onwards were comparable to the total shading factor. It is important to note that the low shading of UV-B radiation across the protective nets (Table S4) might be due to measurement difficulties in the short-wave spectral range (Aphalo, 2016).

Consistent with the sunscreens investigated, none of the protective nets decreased rot severity in addition to the defoliation measures (Figure 6 and Table S8). Protective nets provide a physical barrier which can reduce damage to fruits not merely caused by solar radiation, but can also shield from pathogens (Sharma & Sanikommu, 2018).

5. Viticultural measures vary in terms of their effectiveness

Defoliation is able to determine the level of sunburn necrosis, but also of rot infestation. When conducting ND, sunburn damage was reduced by 84.3 % in comparison to LD at NW, revealing, on average, the highest effectiveness across both growing seasons (Figure 1; Tables 1 and S8). However, ND exhibited the highest severity of rot infestation within each year. LD in turn decreased this damage by 59.5 % across both growing seasons when compared to ND (Figure 2 and Table S8), but recorded the highest levels of sunburn necrosis within each year (Figure 1 and Table S8). Both types of damage were lower than the respective maximum extent at two sites and during each growing season when ED was conducted: The effectiveness in sunburn reduction ranged between 42.8 % and 59.6 % in comparison to LD at RM and NW, respectively. ED was on average more effective during extreme heat waves in 2022 at both sites compared to 2021, respectively (Figure 1; Tables 1, S5 and S8). Additionally, rot infestation was decreased by 68.4 % to 85.3 % when compared to ND at NW and RM, respectively (Figure 2 and Table S8). A similar effectiveness of ED in the reduction of sunburn necrosis (Gambetta *et al.*, 2022) and a lower effectiveness in the prevention of rot infestation (Molitor *et al.*, 2011) have been reported. ED revealed positive impacts against both types of damage, which were independent of experimental sites and growing seasons (Figures 1 and 2; Tables 1 and S8).

Lime in a 2 % concentration decreased sunburn necrosis at NW across both growing seasons by 41.9 % within the LD approaches and was more effective than kaolin in a 5 % concentration (Figure 3 and Table 1), although kaolin is used as an effective sunscreen (Lobos *et al.*, 2015; Teker, 2023). Combining ED and lime revealed an effectiveness in 2021 of 79.2 % in comparison to the maximum extent of sunburn damage, but not in 2022 (Figure 3 and Table 1). This effect might be attributed to the non-extreme and temporarily occurring heat waves in 2021 (Table S5). Consistently, the additional impact of a sunscreen against sunburn necrosis beyond defoliation post-flowering was not recorded within each vintage in the study of Ferrari *et al.* (2017). Thus, ED and application of lime could provide a promising combination, which can be similarly effective as ND, but furthermore protect against rot infestation (Figures 3 and 4; Table 1).

Although the grey, small-meshed *D. suzukii* net and the black, wide-meshed hail net at NW differed in terms of their mean shading factor (Tables S3 and S4), the effectiveness of sunburn prevention by 43.7 % and 44.4 % across both growing seasons was similar (Figure 5; Tables 1 and S8). Both protective nets were comparably effective to lime within the LD approach across both experimental years (Table 1). Oliveira *et al.* (2014) reported halving of shrivelled berries when a white protective net with a shading factor of 23 % was used, indicating a slightly higher effectiveness than the hail net and the *D. suzukii* net. The shading net was on average more effective than lime, *D. suzukii* net and hail net, reducing sunburn necrosis by 63.7 % across both growing seasons (Figure 5; Tables 1 and S8). The results supported colour and mesh sizes of protective nets as essential for the shading factor (Castellano *et al.*, 2008). Combining black and small-meshed net threads of the shading net seems to reveal both the highest mean effectiveness and shading factor of 30 % among the protective nets investigated (Tables 1, S3 and S4). This strategy was comparably effective to ED at NW across both experimental years (Figures 1 and 5; Tables 1 and S8). Overall, the mean effectiveness of the protective nets was increased in 2022, when duration and intensity of heat waves were more extreme and accompanied by drought conditions in comparison to 2021 (Figure 5; Tables 1 and S5).

In conclusion, ED, lime, and protective nets revealed reliable results in terms of sunburn prevention within each experimental year. In contrast, exclusively ED was able to reduce the levels of rot infestation compared to the respective maximum extent during each growing season. The combination of ED with application of sunscreens or shading by protective nets might have a positive impact on both, an additional decrease of sunburn necrosis beyond ED and the prevention of rot infestation at once (Figures 1, 2, 3, 4, 5, and 6; Tables 1 and S8).

6. No impacts on the must weight and vigour of vines

Defoliation, application of sunscreens and shading by protective nets neither influenced total yield including grapes with different levels of damage, berry weight, nor vigour of vines within each growing season at NW (Tables S9, S10, and S11). However, the damage varied between the different measures, affecting grapes in maximum by between 8.2 % to 11.4 % due to sunburn necrosis and by between 11.2 % to 27.6 % due to rot infestation across both years at NW. Reductive effects on yield could be expected if grapes had been separated by quality. While defoliation pre-flowering has been shown to reduce yield (Pastore *et al.*, 2013), partial or intensive defoliation post-flowering, kaolin application (Ferrari *et al.*, 2017), as well as shading nets of different colours up to a shading factor of 40 % had no influence (Martínez-Lüscher *et al.*, 2017). Concerning the influence of defoliation on berry weight, contradictory results have been reported (Dookozlian, 1990; Diago *et al.*, 2010; Ferrari *et al.*, 2017), whereas kaolin application was even able to increase berry weight after intensive defoliation at *véraison* (Ferrari *et al.*, 2017). Negative effects on carbon

balance can be expected if vines are shaded excessively for a longer period of time (Greer *et al.*, 2011). Seasonal impacts recorded a higher total yield, berry weight and vigorous growth in 2021 when compared to 2022 (Tables S9, S10, and S11), potentially due to a higher water supply of the vines (Table S5).

Must weights at harvest were not affected by the viticultural measures within each year (Table 2). According to Ferrari *et al.* (2017), defoliation post-flowering resulted in an increase of soluble solids compared to ND, but the effect was not consistent among the vintages for defoliation at *véraison*. While kaolin did not impact sugar concentration in the studies of Ferrari *et al.* (2017) and Teker (2023), shading of vines by 75 % using a black net showed a delay in maturation (Lu *et al.*, 2021). The decrease of total acidity within the ED approaches in each growing season was likely the result of malic acid degradation when compared to ND, respectively (Table 2), due to the longer exposure to solar radiation accompanied by increasing berry temperatures (Lakso & Kliewer, 1975). Application of lime increased the pH value in comparison to both defoliated approaches without sunscreen in each year (Table 2) and might contribute to a negative impact on preferred must characteristics. Overall, the higher levels of malic acid and total acidity, as well as the lower pH value in 2021 compared to 2022 (Table 2), can be attributed to lower air temperatures (Table S5; Lakso & Kliewer, 1975; Ganichot, 2002; De Orduña, 2010). Sunburn and rot damage on grapes are able to affect the quality of wines (Ribéreau-Gayon, 1983; Diago *et al.*, 2010; Rustioni *et al.*, 2023; Szmania *et al.*, 2023), but this issue was not addressed in the present study.

CONCLUSION

Regarding various phytosanitary benefits and quality improvements of grapes, defoliation is an effective and low-cost viticultural tool. However, grapes are more sensitive to sunburn damage when defoliation is timed incorrectly. The field experiments of this study showed that early defoliation between the end of flowering and fruit set leads to both less severe sunburn necrosis and rot infestation on ‘Riesling’ grapes in comparison to the respective maximum extent at two experimental sites and within each growing season. Application of lime onto grapes and shading by protective nets were able to decrease sunburn damage after late defoliation at bunch closure within each experimental year. The combined effect of early defoliation and application of lime against sunburn necrosis was exclusively recorded within one growing season and needs to be further investigated. Future studies have to evaluate possible effects of viticultural measures on wine quality across several vintages.

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