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Olu-Olusegun, O. F., Farrell, A., Monaghan, J., & Kettlewell, P. (2025) 'Film-Forming and Metabolic Antitranspirants Reduce Potato Drought Stress and Tuber Physiological Disorders', *Agronomy*, 15(7), article number 1564.

agronomy

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Film-Forming and Metabolic Antitranspirants Reduce Potato Drought Stress and Tuber Physiological Disorders

Oluwatoyin Favour Olu-Olusegun [1,*], Aidan Farrell [2], James Monaghan [1] and Peter Kettlewell [1,*]

[1] Crop Science Group, Harper Adams University, Newport, Shropshire TF10 8NB, UK; jmonaghan@harper-adams.ac.uk

[2] Department of Life Sciences, The University of the West Indies, St. Augustine Campus, St. Augustine, Trinidad and Tobago; aidan.farrell@uwi.edu

* Correspondence: folu-olusegun@live.harper.ac.uk (O.F.O.-O.); pskettlewell@harper-adams.ac.uk (P.K.)

Abstract

Potatoes are highly sensitive to drought, particularly during tuber initiation. This study aimed to evaluate the effectiveness of film-forming (Vapor Gard [VG]) and metabolic (abscisic acid [ABA]) antitranspirants in mitigating drought stress and reducing tuber physiological disorders in four potato varieties. Two experiments examined the effects of VG and ABA antitranspirants on drought-stressed potato plants of four varieties (Challenger, Markies, Nectar, and Russet Burbank) grown in pots in a polytunnel (semi-controlled environment). Experiment 1 imposed severe drought by withholding irrigation until 70% of the available water content was depleted (reaching 15–17% volumetric water content within ~15 days), while Experiment 2 featured gradual drought stress from tuber initiation, with the soil volumetric water content declining to <10% over 30 days. Antitranspirants were applied at the start of the tuber initiation and two weeks later to assess their impact on the soil volumetric water content, stomatal conductance, relative water content, yield, and tuber physiological disorders. Drought significantly reduced the soil and plant water status, tuber yield, and quality across both experiments, with more severe effects observed in Experiment 1. VG and ABA had repeatable effects in both experiments and in all varieties, reducing water stress by preventing a large reduction in the relative water content during the tuber initiation and bulking stages. Both antitranspirants improved the tuber appearance by reducing the tuber skin disorder of russeting in the susceptible Challenger variety in both experiments, with VG being more effective than ABA. Beneficial reductions in the effects of drought from antitranspirants were also recorded in the volumetric water content, stomatal conductance, yield, and jelly end rot but not consistently in all varieties and in both experiments. The results show that antitranspirants have the potential to minimise water stress in droughted potatoes and subsequently reduce the physiological disorder of russeting and improve the tuber appearance of the Challenger variety.

Keywords: abscisic acid; di-1-p-menthene; leaf water status; film-forming polymer; jelly end rot; post-harvest storage; relative water content; *Solanum tuberosum*; stomatal conductance; tuber russeting; Vapor Gard; volumetric water content; yield

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Academic Editor: Alfredo Emilio Rubio Casal

Received: 12 May 2025
Revised: 20 June 2025
Accepted: 23 June 2025
Published: 27 June 2025

Citation: Olu-Olusegun, O.F.; Farrell, A.; Monaghan, J.; Kettlewell, P. Film-Forming and Metabolic Antitranspirants Reduce Potato Drought Stress and Tuber Physiological Disorders. *Agronomy* **2025**, *15*, 1564. https://doi.org/10.3390/agronomy15071564

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1. Introduction

Potatoes (*Solanum tuberosum* L.) are a crucial food source, ranking fourth in global production [1]. They contribute significantly to food security and economic stability, particularly in developing countries [2]. However, climate change poses a severe threat.

Rising temperatures and drought conditions are leading to potential crop losses of up to 50% [3]. Research [4] indicates that potato yields decline by 2% for every 10% decrease in rainfall in non-irrigated sites.

Potatoes, as a crop with a shallow root system and high water needs, are particularly vulnerable to drought stress [5]. Drought disrupts various physiological processes, leading to stunted growth, a reduced yield, and increased disease susceptibility [6]. Additionally, drought can negatively impact the quality and storage life of potato tubers, increasing the risk of disorders like russeting and internal bruising [7–9]. Some of these disorders, such as russeting, can be detected at harvest, while others, such as internal browning, may develop or worsen during storage [10]. Minimising these disorders is essential for reducing post-harvest losses and ensuring food security.

Research across multiple crops suggests that antitranspirants can help mitigate drought stress in plants by reducing the stomatal conductance and maintaining the plant water status (i.e., a higher leaf relative water content and leaf water potential) [11]. In potatoes specifically, antitranspirant applications have reduced transpiration rates by 38–50% under greenhouse conditions [12], improved the yield and marketable tubers by 20% and 1.7%, respectively [13], and improved water relations and photosynthetic activities during drought episodes [14]. Field studies have shown that antitranspirant treatments on potatoes increased the plant height, dry matter, and yield under water stress conditions [15]. Antitranspirants are categorised into three main types: reflective, film-forming, and metabolic (stomata-closing). Metabolic antitranspirants are a group of hormones or hormone-like substances that influence stomatal closure [16]. The most prominent member of this group is abscisic acid (ABA). Exogenous ABA is a stomata-closing antitranspirant and has shown effectiveness in reducing the negative effects of drought on crops such as wheat [17] and artichoke [18]. However, its effectiveness is temporary, lasting for fewer than seven days [19]. In contrast, Vapor Gard (VG), a film-forming antitranspirant, suppresses stomatal conductance and reduces water loss by coating the leaf surface. Studies indicate VG's effects can persist for 20–25 days, providing prolonged drought protection through sustained reductions in gas exchange compared to ABA over extended drought periods [20]. VG's longer-lasting effects led to diverse crop-specific benefits. In potato crops, VG applications have shown promise. Byari [12] demonstrated that VG was among the most effective antitranspirants for reducing transpiration in potato varieties. VG applications have been shown to increase the leaf water potential in drought-stressed potato plants, leading to an improved calcium accumulation in tubers and reduced tuber necrosis [21]. In drought-stressed oilseed rape, a VG treatment increased pod numbers and the seed biomass [20]. For viticulture, a VG application delayed sugar accumulation in grapes [22,23], which is beneficial for controlling alcohol levels in wine production.

The research on the use of antitranspirants in potatoes is limited. While some studies have shown positive results, such as an improved water use efficiency and yield [15], others emphasise the need for context-specific applications, as the effectiveness of antitranspirants can vary based on the type used, application method, and potato variety [12]. Despite advancements, some studies report inconsistent or limited effects of antitranspirants on plants under drought conditions [11]. A critical knowledge gap exists regarding whether an antitranspirant application directly reduces the incidence and/or severity of specific physiological disorders in potato tubers. Understanding this aspect is crucial, as these disorders significantly impact marketability.

Our central hypothesis is that applying antitranspirants during drought stress mitigates physiological damage in potato plants and improves the yield and tuber quality by reducing physiological disorders.

2. Materials and Methods

2.1. Research Environment and Planting Materials

Two pot experiments were conducted in a polytunnel at Harper Adams University (HAU), Newport, Shropshire, UK (52°46′ N, 2°25′ W), in 2023. Experiment 1 (Exp 1) was planted on 6 April 2023 and Experiment 2 (Exp 2) on 6 July 2023. The experiments had similar experimental design and duration. The aim was to evaluate the effects of different irrigation and antitranspirant (AT) treatments on the growth and quality of four potato varieties. Two commercially available antitranspirants were used: VG and ABA. VG is a film-forming product containing 96% di-1-p-menthene (Pinolene®, Miller Chemicals and Fertilizer, Hanover, PA, USA), a pine resin-derived terpene polymer that creates a flexible film on leaf surfaces to reduce water loss. It is widely marketed for use in horticulture and agriculture to minimise drought stress [24]. ABA (20% s-abscisic acid, Valent Biosciences, Libertyville, IL, USA), a naturally occurring plant hormone, acts as a metabolic antitranspirant by inducing stomatal closure and temporarily reducing transpiration. Commercial ABA formulations are available and used by grape growers to improve fruit colouring, initiate earlier harvests, and increase marketable yield [25]. The planting medium for both experiments consisted of John Innes No. 2 compost, a pre-mixed growing medium containing loam, peat, coarse sand, and base fertiliser. This compost was sourced from LBS Worldwide Ltd. (Colne, Lancashire, UK). Each pot, measuring 40 L with a diameter of 50 cm and a height of 36 cm, was filled with approximately 20 kg of compost. Water was added to achieve a volumetric water content (VWC) of 40%, which corresponds to approximately 95% field capacity (FC).

Four potato varieties were sourced from different suppliers: Challenger, a processing variety, from HZPC (Scunthorpe, UK); Markies, also a processing variety, from Agrico (Emmeloord, The Netherlands); Nectar, a pre-pack (fresh market) variety, from IPM potato group (Dublin, Ireland), which is not stored for prolonged periods, and thus has different exposure to storage disorders; and Russet Burbank, widely used for both pre-pack and processing purposes, from McCains (Montrose, Scotland, UK). A single potato seed tuber was planted per pot. Varietal susceptibility to physiological disorders is well-documented in the literature. Russet Burbank is widely reported as susceptible to internal and external defects, including sugar end/jelly end rot, especially under heat and water stress [26,27]. Challenger shows moderate susceptibility to internal disorders and significant vulnerability to tuber skin disorders [28]. In contrast, Nectar and Markies have less documented evidence; industry reports suggest resistance to skin disorders [29,30].

2.2. Experimental Design

All the pots in the two experiments were arranged on benches in a randomised complete block design to control for potential spatial variation within the polytunnel. The experiment utilised a 4 × 4 factorial design, including the four varieties and four irrigation/AT levels: irrigated (IRR), drought no AT (DT no AT), drought VG (DT + VG), and drought ABA (DT + ABA). DT + VG and DT + ABA are considered part of the DT + ATs category, representing drought conditions with AT applications. Each treatment combination was replicated in five blocks, with four pots per treatment in each block. This setup resulted in 80 pots (4 varieties × 4 treatments × 5 blocks). This study was conducted twice (Exp 1 and Exp 2), producing a total of 160 pots across both experiments.

2.3. Monitoring Temperature and Humidity with Tinytag Data Logger

A Tinytag data logger (Gemini Ultra 2 logger, Chichester, West Sussex, UK) was placed in the polytunnel to record daily minimum and maximum temperatures (°C) and relative humidity (%), to monitor the climate conditions. The logger was located at the canopy height in the polytunnel and recorded data at one-hour intervals throughout the growing season. Weekly averages for temperature and humidity were calculated and visualised. Summary statistics for environmental conditions are provided in the results section.

2.4. Soil Moisture Measurements, Irrigation Regimes, and Drought Imposition

Changes in the VWC of the compost were measured using a FieldScout TDR 100 time-domain reflectometry (TDR) probe (Spectrum Technologies, Inc., Aurora, IL, USA) at 2–3-day intervals throughout the growing season. The probe was inserted to a depth of 20 cm to obtain VWC measurements. A soil water–retention curve of John Innes No. 2 compost was used to determine the VWC at field capacity and permanent wilting point (PWP), which were approximately 42% and 7.5%, respectively [31]. This resulted in an available water content (AWC) of 34.5% (FC—PWP). Before tuber initiation, all pots were well irrigated with 2 L of water every other day to ensure optimal growth until tuber initiation (~50–70 Days After Planting [DAP]). Throughout the experiment, irrigated plants received a top-up of 2 L of water every other day, increasing to 3 L during periods of hot weather, to maintain approximately 40% VWC (~95% FC). Drought stress was initiated at 56 DAP in Exp 1 and at 35 DAP in Exp 2.

Drought stress was initiated at the onset of tuber initiation, which was assessed by subsampling extra plants. For drought treatments (DT no AT, DT + VG, DT + ABA), watering was stopped at tuber initiation, allowing 70% of plant AWC to deplete. Drought stress was then maintained at 30% AWC (15–17% VWC, Table 1), from approximately −0.25 to −0.30 MPa [31] for the droughted pots. After the antitranspirant application, the drought-stressed pots were re-watered and adjusted as needed, based on the VWC reading, every other day to maintain the targeted AWC and ensure consistent drought stress levels. In the experiments, the required volume of water to adjust soil moisture in irrigated and drought-stressed pots was determined using the volumetric water content (VWC) difference between the current and target levels, using the following formula:

$$V\text{ water} = V \times (\theta\text{ target} - \theta\text{ current})$$

where

V water is the volume of water to add (L);
V is the volume of the soil/compost (L);
θ target is the target volumetric water content (%);
θ current is the current volumetric water content (%).

Table 1. A summary of the irrigation management, antitranspirant application, and physiological assessments for the two experiments.

Experiment 1 Week	Experiment 2 Week	Stage	DAP at Drought Initiation	% of AWC	AT	Assessments
1–4	1–2	Establishment	-	100%	-	-
5–8	3–6	Stolon initiation	-	100%	-	-
9–13	6–10	Tuber initiation	56 (Exp 1) 35 (Exp 2)	Dry-down	-	Porometer
11 (June 22)	8 (Sept. 2)	-		30%	Spray 1	Porometer
12–13	10	Tuber initiation		30%	Spray 2	Porometer
14–19	11–16	Tuber filling		30%		RWC
20–24	17–20	Maturity		0%		-
25	21	Maturity		0%	-	Harvest

2.5. Antitranspirant Application

Antitranspirants were first applied 1–2 weeks after drought initiation, during the ongoing tuber initiation phase. Two antitranspirants were used: Vapor Gard (96% di-1-p-menthene, VG; Miller Chemicals and Fertilizer, Hanover, PA, USA) at 5 mL/L and ABA (20% s-abscisic acid, Valent Biosciences, Libertyville, IL, USA) at 0.15 g/L, diluted in water only without adjuvant. Both were applied using a hand sprayer (Hozelock Exel, Arnas, France) when AWC reached 30%. Antitranspirants were sprayed twice per experiment, first at tuber initiation (30 days after emergence) and again after 2 weeks (Table 1). The control was unsprayed to represent a typical farm crop, which would not have an antitranspirant.

To prevent spray drift and ensure that only targeted plants received antitranspirants, plants were covered with custom-made four-cornered paper boxes wrapped in nylon before application. To avoid cross-contamination, different tanks were used for each type of AT. Antitranspirants were sprayed uniformly on the adaxial surface of the plant canopy, ensuring that all leaves were thoroughly covered until all leaf surfaces were visibly wet but not to the point of run-off.

2.6. Stomatal Conductance Measurements

In Exp 1, stomatal conductance ($g_{s,}$ mmol m^{-2} s^{-1}) was measured using a transient state diffusion porometer (AP4 Delta-T Devices, Cambridge, UK, version 3.1), and in Exp 2, an SC-1 Leaf porometer (Meter Group, Inc., Pullman, WA, USA) was used. Calibration was performed before each measurement using the manufacturer's calibration plate to ensure accuracy. Calibration error did not exceed 5%. Stomatal conductance was measured in mmol m^{-2} s^{-1} on the abaxial surface of the youngest fully expanded leaflet of the top canopy for each pot. Three leaflets were sampled per pot, selected from three different compound leaves, and the mean value was used for analysis. Measurements were taken once before tuber initiation and 2–3 times weekly after antitranspirant application, targeting the peak stress periods. All measurements were conducted between 10:00 a.m. and 2:00 p.m., a window selected to capture peak stomatal activity under stable light and temperature conditions and minimise diurnal variability in stomatal conductance, as stomatal conductance in potato and other species typically peaks mid-morning and remains high until early afternoon [32,33]. Stomatal conductance measurements were completed within 30 min per block once processing began.

2.7. The Relative Water Content (RWC) of the Leaves

RWC was assessed using whole leaflets, following the method of [34]. Three fully expanded leaflets from the top canopy of each pot, selected from three different compound leaves, were collected. Each sample was placed in an airtight plastic container and immediately in a picnic cooler with ice packs to minimise water loss. Fresh weight (FW) was measured within 1 h of harvest. FW measurements were completed within 15–20 min per block once processing began. The leaflets were submerged in distilled water for 24 h and placed in the refrigerator at 4 °C to reach full turgidity. After soaking, the leaflets were gently dried with filter paper and weighed to obtain the turgid weight (TW). Leaflets were dried in an oven at 80 °C for 48 h. Dried leaflets were allowed to cool and then weighed to measure the dry weight (DW). RWC was measured at 14 weeks after planting (91 DAP) in Exp 1 and 11 weeks (77 DAP) in Exp 2, corresponding to early tuber filling stages. The relative water content was calculated using the formula:

$$\text{RWC (\%)} = [(FW - DW)/(TW - DW)] \times 100$$

where *RWC* (%) = relative water content percentage;

FW = fresh weight;

TW = turgid weight;
DW = dry weight [34].

2.8. Yield Component Analysis and Potato Physiological Disorder Assessment

At maturity, all tubers were harvested by hand, washed free of soil, and surface-dried for 24 h to remove excess moisture before weighing. A high-precision digital balance (KERN FKB 16K0.1, KERN & Sohn GmbH, Balingen, BW, Germany), with a maximum capacity of 16,100 g and a resolution of 0.1 g, was used to measure the total tuber weight per pot. The number of tubers per pot was also counted, and the average weight per tuber was calculated by dividing the total tuber weight by the number of tubers per pot.

Physiological disorders, including russeting, internal brown spot/necrosis, jelly end rot (JER), hollow heart, greening, black heart, and mechanical bruising, were visually assessed [35,36] on a random subsample of 2–6 tubers per plant before and after storage. Each tuber was assessed for physiological disorders using a presence/absence classification. External skin disorders (e.g., russeting) were recorded as present if more than 5% of the surface area exhibited visible symptoms, aligning with industry standards for marketable tuber quality. Internal defects (e.g., JER) were evaluated by bisecting tubers longitudinally and inspecting for discolouration or lesions; any visible symptoms, including small lesions (~1–2 mm), were recorded as affected. Processing varieties (Challenger, Markies, Russet Burbank) were stored at 8 °C +/− 0.5 °C in a commercial storage facility located in Newport, Shropshire, and treated with the sprout inhibitor 1,4SIGHT® (Dimethylnaphthalene, DormFresh Ltd., Perth, UK). In contrast, the fresh market variety, Nectar, was stored at a lower temperature (3.5 °C) in a cold room at Harper Adams University without sprout control. This difference in storage conditions adheres to commercial storage standards and temperature settings for processing and fresh market varieties.

The harvested tubers were stored for 9 and 5 months for Exps 1 and 2, respectively. Markies and Nectar showed negligible disorders before and following storage and were excluded from subsequent statistical analysis of storage disorders.

2.9. Statistical Analysis

Data were analysed using Genstat 23rd edition (VSN International, Hemel Hempstead, UK; https://vsni.co.uk/software/genstat/) and R software version 4.4.1 (R Core Team, Vienna, Austria; https://www.r-project.org). A two-way ANOVA with orthogonal contrasts was performed to evaluate treatment effects (i.e., IRR vs. DT [sum of DT no AT, DT + VG, DT + ABA], DT no AT vs. DT + ATs [sum of DT+ VG and DT + ABA], DT + VG vs. DT + ABA) using Genstat 23rd edition. Repeated measures ANOVA was used for soil moisture content and stomatal conductance data. Normality was assessed using residual histograms and normal Q–Q plots. Homogeneity of variance was checked using residual vs. fitted values plots. Results are presented as means with standard error of difference (SED).

Fisher's exact test was conducted separately for each variety (before and after storage) to compare the proportion of tubers with physiological disorders across treatments using the same orthogonal contrasts. This test was selected for its accuracy with small sample sizes.

3. Results

3.1. Temperature and Relative Humidity

The environmental conditions within the polytunnel varied between the two experiments. In Exp 1, the mean daily air temperature was 23.4 °C, fluctuating between 8.7 °C and 35.5 °C. The relative humidity varied between 41% and 90% (Figure 1a). These high temperatures and variable humidity levels likely contributed to the slower growth and delayed tuber development observed. In contrast, Exp 2 experienced more favourable growing conditions, with a mean daily air temperature of 18.8 °C, fluctuating between 13.7 °C and 33.5 °C. The relative humidity was generally high, ranging between 50% and 100% (Figure 1b).

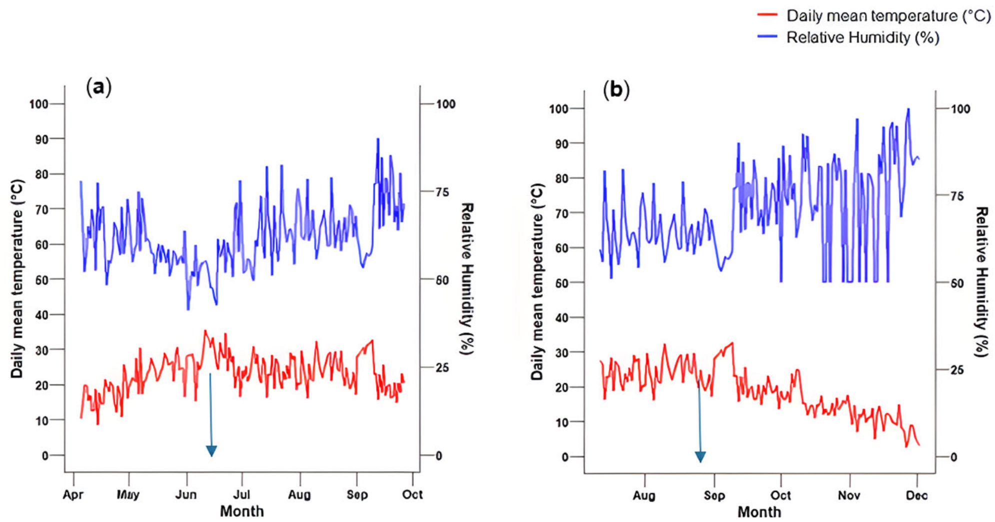

Figure 1. The daily mean temperature (°C, red line) and relative humidity (%, blue line) during the growing season of potato plants in Experiment 1 (**a**) and Experiment 2 (**b**), respectively. The arrow represents the tuber initiation and the day of spraying antitranspirants. Tick marks on the *x*-axis indicate the start of each month. Experiment 1 started on 5 April, and Experiment 2 started on 12 July.

3.2. Volumetric Water Content (VWC)

The VWC varied significantly between irrigated pots and droughted pots over time (Treatment; Time × Treatment; Table 2) but not between varieties or ATs in Exp 1. However, in Exp 2, VG and ABA exhibited a significant difference in their effects on the VWC under drought; despite this, there was no average AT efficacy in comparison to DT. The mean VWC for VG-treated plants was 14.45%, whereas for ABA-treated plants it was 14.50%. Although the difference in means was small, it was statistically significant. Under well-watered (IRR) conditions, the soil had an average VWC of 22%, above 50% of the FC in Exp 1 (Figure 2a–d). In contrast, drought conditions dried down quickly (~15 days), resulting in an average VWC of < 10%, with substantial fluctuations between 3% and 10% over time, i.e., values close to the PWP. This level was sustained until the end of the experiment (Figure 2a–d). Exp 2 presented a less severe drought scenario compared to Exp 1. Under IRR conditions, the soil VWC was ~30% (closer to FC), while DT plants took approximately 30 days to dry down, reaching an average of <10% by the tuber initiation with fluctuations between 3% and 10% until maturity (Figure 2e–h).

Table 2. Probability values from ANOVA for volumetric water content (VWC) and stomatal conductance (gs), as affected by irrigation (IRR) and antitranspirant (AT) in two experiments. Bold numbers indicate significant differences at $p < 0.05$.

Experiment	Factors	*d.f.*		*p* Values	
		VWC	gs	VWC	gs
Exp 1	Treatment	3	3	**<0.001**	**<0.001**
	Variety	3	3	0.414	0.435
	Treatment × Variety	9	9	0.887	0.651
	Time	17	8	**<0.001**	**<0.001**

Table 2. *Cont.*

Experiment	Factors	*d.f.*		*p* Values	
		VWC	gs	VWC	gs
	Time × Treatment	51	24	**<0.001**	**<0.001**
	Time × Variety	51	24	0.555	0.895
	Time × Treatment × Variety	153	72	0.921	0.955
	CV (%)	9.0	17.4		
	Contrast *p* values				
	IRR vs. DT	1	1	**<0.001**	**<0.001**
	DT vs. AT	1	1	0.725	**<0.001**
	VG vs. ABA	1	1	0.952	0.881
	Interaction contrast *p* values				
	Variety × Treatment	9	9	0.889	0.651
	Variety × IRR vs. DT	3	3	0.585	0.694
	Variety × DT vs. AT	3	3	0.861	0.878
	Variety × VG vs. ABA	3	3	0.677	0.205
	Time × Variety	51	24	0.508	0.895
	Time × Treatment	51	24	**<0.001**	**<0.001**
	Time × IRR vs. DT	17	8	**<0.001**	**<0.001**
	Time × DT vs. AT	17	8	0.26	**0.001**
	Time × VG vs. ABA	17	8	0.97	0.818
	Time × Variety × Treatment	153	72	0.903	0.955
	Time × Variety × IRR vs. DT	51	24	0.368	0.703
	Time × Variety × DT vs. AT	51	24	0.976	0.999
	Time × Variety × VG vs. ABA	51	24	0.7906	0.5247
Exp 2	Treatment	3	3	**<0.001**	**<0.001**
	Variety	3	3	0.312	0.199
	Treatment × Variety	9	9	0.217	0.228
	Time	12	6	**<0.001**	**<0.001**
	Time × Treatment	36	18	**<0.001**	**<0.001**
	Time × Variety	36	18	0.394	0.162
	Time × Treatment × Variety	108	54	0.942	0.97
	CV (%)	10.1	9.0		
	Contrast *p* values				
	IRR vs. DT	1	1	**<0.001**	**<0.001**
	DT vs. AT	1	1	0.205	0.14
	VG vs. ABA	1	1	**0.015**	0.439
	Interaction contrast *p* values				
	Variety × Treatment	9	9	0.329	0.092
	Variety × IRR vs. DT	3	3	0.202	0.073
	Variety × DT vs. AT	3	3	0.943	0.099
	Variety × VG vs. ABA	3	3	0.156	0.553
	Time × Variety	33	18	0.648	0.071
	Time × Treatment	33	18	**<0.001**	**<0.001**
	Time × IRR vs. DT	11	6	**<0.001**	**<0.001**
	Time × DT vs. AT	11	6	0.42	0.099
	Time × VG vs. ABA	11	6	0.271	0.18
	Time × Variety × Treatment	99	54	0.952	0.854
	Time × Variety × IRR vs. DT	33	18	0.626	0.754
	Time × Variety × DT vs. AT	33	18	0.893	0.736
	Time × Variety × VG vs. ABA	33	18	0.9024	0.618

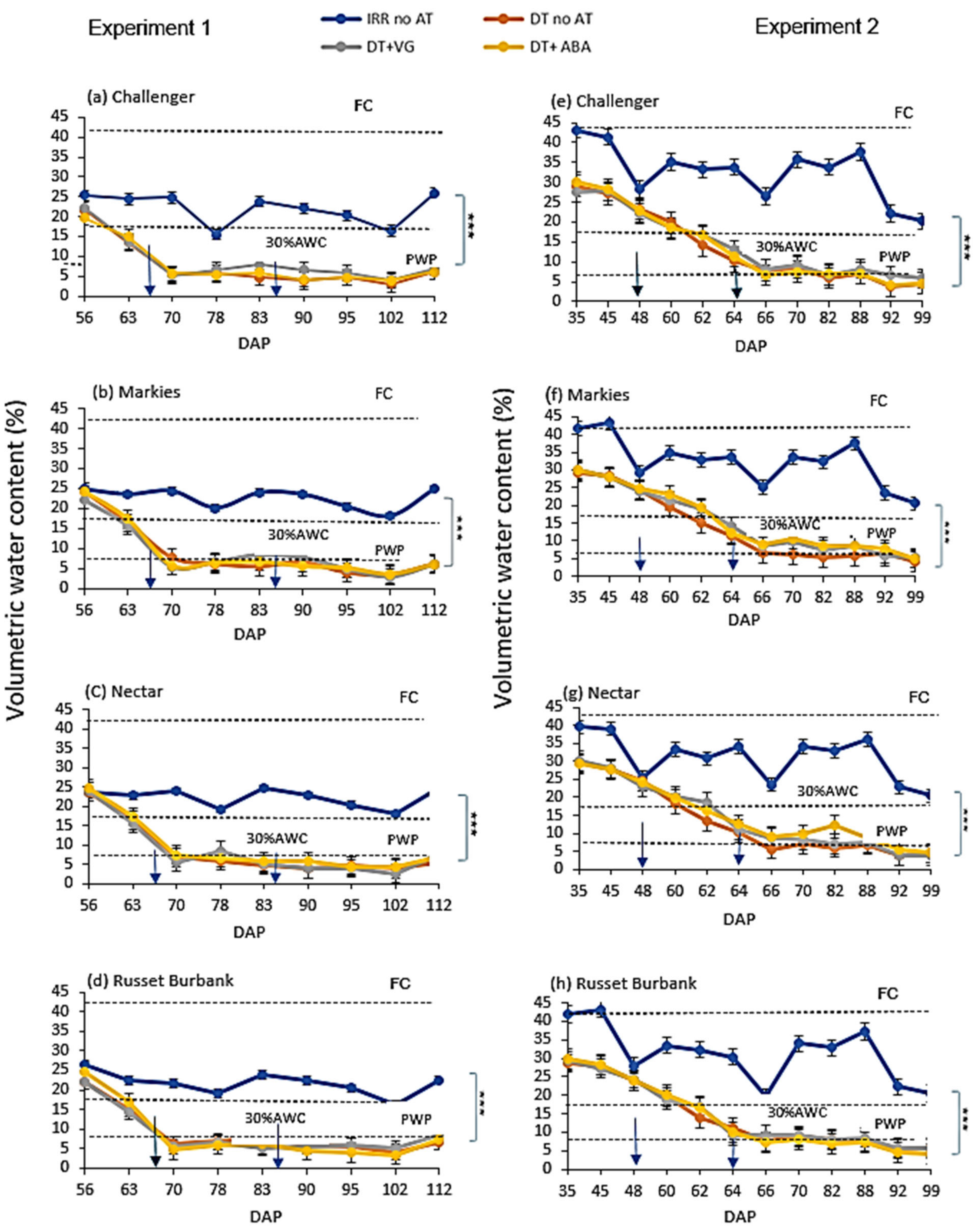

Figure 2. The soil volumetric water content (VWC) for Exp 1 and 2 for (**a**,**e**) Challenger; (**b**,**f**) Markies; (**c**,**g**) Nectar; and (**d**,**h**) Russet Burbank pots under well-watered (IRR) and water-stressed (Drought no AT, Drought + VG and Drought + ABA) conditions before and after spraying antitranspirants. Arrows represent the day of spraying antitranspirants. The target VWC of water stress treatments, 30% available water content (30% AWC). Data are means of replicates (n = 5). Error bars represent the Standard Error of Difference (SED). DF = 60. FC is Field Capacity, and PWP is Permanent Wilting Point. Where IRR = Irrigated, DT = Drought, AT = Antitranspirant, VG = Vapor Gard, and ABA = Abscisic Acid. Asterisks (***) represent significant differences in IRR compared to DT and ATs according to Tukey's test (p = 0.05).

3.3. Stomatal Conductance

The drought stress significantly reduced the stomatal conductance across all varieties in both experiments (Table 2). In Exp 1, all drought treatments decreased the stomatal conductance compared to well-watered plants, with DT no AT exhibiting a 61% reduction. There was a notable time–treatment interaction, likely due to the increasing difference between irrigated and drought-stressed treatments as the drought severity increased over time (Figure 3). The antitranspirant application gave a smaller drought-induced reduction in stomatal conductance compared to DT no AT, with a notable time–treatment interaction observed, likely due to the difference between DT no AT and AT treatments reducing over time. In Exp 2, DT no AT exhibited a 44% reduction in stomatal conductance compared to well-watered plants. As observed in Exp 1, a significant time–treatment interaction was also observed in Exp 2 as the drought severity increased over time. The effect of antitranspirants was not significant in Exp 2, with stomatal conductance values for DT + VG and DT + ABA being similar to those for DT without antitranspirants.

3.4. Relative Water Content (RWC)

The drought stress significantly reduced the RWC across all potato varieties in both experiments. In Exp 1, DT no AT, the RWC decreased compared to well-watered conditions ($p < 0.001$, Table 3). The mean RWC was 88.1% under irrigation and 52.6% for DT no AT. The application of ATs significantly influenced the RWC across potato varieties. VG-treated plants showed a 44.7% increase in RWC compared to DT no AT plants, while the ABA treatment resulted in a 25.7% increase on average. The difference between VG and ABA treatments was significant and was most marked in Challenger, which did not respond to ABA. In Exp 2, DT no AT decreased compared to well-watered conditions (Table 3). The mean RWC was 89.1% under irrigation and 55.8% for DT no AT. The application of VG and ABA significantly increased the RWC in drought-stressed plants. Although VG and ABA treatments did not differ significantly, a marginal significance was noted between variety–treatment interactions, possibly because it appeared that ABA did not affect the RWC in two varieties. This suggests potential subtle differences in varietal responses to treatments, particularly under different environmental conditions.

3.5. Yield

In Exp 1 (Table 4), the yield results showed that the variety effect was significant ($p = 0.002$), with Russet Burbank achieving the highest yield under irrigation (1290 g/plant) and Markies the lowest (781 g/plant). Drought conditions and AT treatments significantly affected tuber yields across all potato varieties. Irrigated plants consistently produced higher yields than those under drought stress, with a 43% increase. The overall effect of ATs on the yield under drought conditions was not statistically significant. However, a significant interaction between the potato variety and treatment was observed, indicating that varieties responded differently to treatments. For example, under DT no AT, Russet Burbank had a 42.6% reduction in yield, but Markies lost only 14.5%. DT + VG-treated plants showed an 11.3% increase across all varieties compared to DT no AT, but among AT treatments, DT + VG significantly outperformed DT + ABA in only three varieties (Markies, Nectar, and Russet Burbank), whereas in Challenger, ABA was superior to VG.

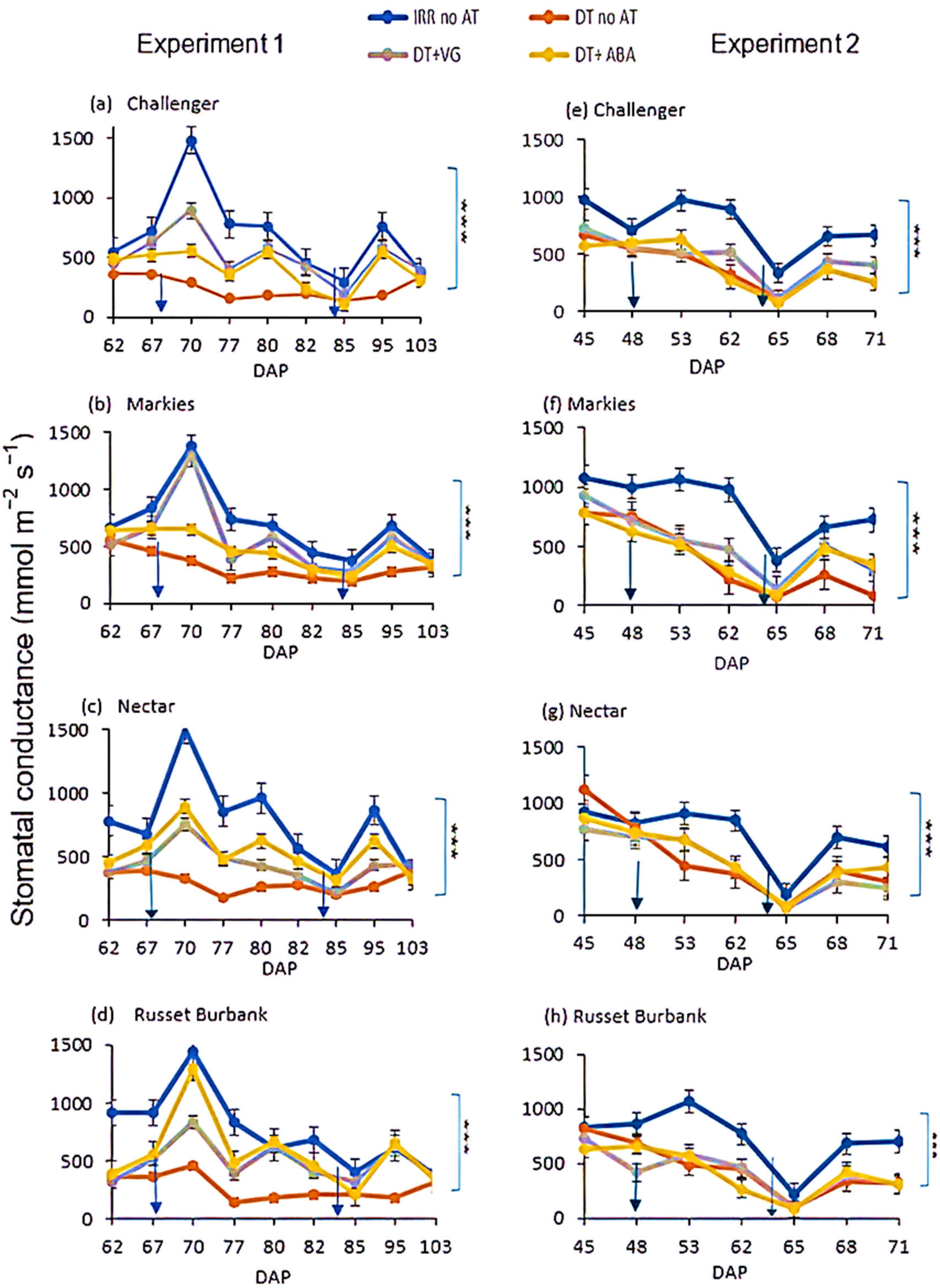

Figure 3. The stomatal conductance for Exp 1 and 2 for (**a**,**e**) Challenger; (**b**,**f**) Markies; (**c**,**g**) Nectar; and (**d**,**h**) Russet Burbank pots under well-watered (IRR) and water-stressed (Drought no AT, Drought + VG and Drought + ABA) conditions before and after spraying antitranspirants. Arrows represent the day of spraying antitranspirants. T. Data are means of replicates (n = 5). Error bars represent the Standard Error of Difference (SED). DF = 60. FC is the Field Capacity, and PWP is the Permanent Wilting Point. Where IRR = Irrigated, DT = Drought, AT = Antitranspirant, VG = Vapor Gard, and ABA = Abscisic Acid. Asterisks (***) represent significant differences in IRR compared to DT and ATs according to Tukey's test (p = 0.05).

Table 3. The relative water content (RWC) of four potato varieties under different irrigation and antitranspirant treatments across two experiments. Bold numbers indicate significant differences at $p < 0.05$. Where IRR = Irrigated, DT = Drought, AT = Antitranspirant, DT + ATs = Drought + Antitranspirants, VG = Vapor Guard, and ABA = Abscisic Acid. Data are means of replicates (n = 5).

		Experiment 1	Experiment 2
Variety	**Treatment**	**RWC (%)**	**RWC (%)**
Challenger	IRR no AT	85.8	96.3
	DT no AT	59.6	54.9
	DT + VG	83.7	84.7
	DT + ABA	58.8	52.6
Mean		72.0	72.1
Markies	IRR no AT	91.8	85.1
	DT no AT	53.5	57.8
	DT + VG	79.7	75.3
	DT + ABA	64.5	64.9
Mean		72.4	70.8
Nectar	IRR no AT	85.9	85.9
	DT no AT	47.0	51.4
	DT + VG	74.3	92.7
	DT + ABA	68.3	77.3
Mean		68.9	76.8
Russet Burbank	IRR no AT	88.9	89.1
	DT no AT	50.1	58.9
	DT + VG	66.7	69.5
	DT + ABA	72.6	46.9
Mean		69.6	66.1
Mean over varieties	IRR no AT	88.1	89.1
	DT no AT	52.6	55.8
	DT + VG	76.1	80.6
	DT + ABA	66.1	60.4
CV%		19.7	20.8
SED	d.f		
Treatment	60	4.41	4.70
Variety		4.41	4.70
Variety × Treatment		8.83	9.40
p values			
Treatment		**<0.001**	**<0.001**
Variety		0.816	0.164
Variety × Treatment		0.472	0.075
Contrast *p* values			
IRR vs. DT		**<0.001**	**<0.001**
DT no AT vs. DT + ATs		**<0.001**	**<0.001**
DT + VG vs. DT + ABA		0.003	0.322
Interaction contrast *p* values			
Variety × IRR vs. DT		0.208	0.905
Variety × DT no AT vs. DT + ATs		0.369	0.310
Variety × DT + VG vs. DT + ABA		**0.039**	0.205

In Exp 2 (Table 4), the yield differences between varieties were similar to those in Exp 1, with Russet Burbank being the highest and Markies the lowest, but these were not significant due to the greater variability in this experiment. Irrigated plants maintained higher yields than those under drought stress, with a 73.8% increase in Exp 2. There was a notable difference in how varieties responded to drought stress. For instance, Russet Burbank's yield decreased by 57.7% under DT no AT conditions compared to irrigated plants, while Markies' yield decreased by only 14.5%. Interestingly, the application of ATs did not significantly affect the yield under drought conditions; hence, no significant difference was observed among VG compared with ABA treatments. This suggests that the AT effectiveness may vary depending on environmental conditions, such as the severity of the drought stress.

Table 4. The yield of potato tubers from four potato varieties under different irrigation and antitranspirant treatments across two experiments. Bold numbers indicate significant differences at $p < 0.05$. Where IRR = Irrigated, DT = Drought, A = Antitranspirant, DT + ATs = Drought + Antitranspirants, VG = Vapor Guard, and ABA = Abscisic Acid**.** Data are means of replicates ($n = 5$).

		Experiment 1	**Experiment 2**
Variety	**Treatment**	**Weight (g/plant)**	**Weight (g/plant)**
Challenger	IRR no AT	961	1296
	DT no AT	771	943
	DT + VG	872	732
	DT + ABA	999	942
Mean		901	978
Markies	IRR no AT	781	1001
	DT no AT	668	856
	DT + VG	700	694
	DT + ABA	629	731
Mean		695	820
Nectar	IRR no AT	1135	1589
	DT no AT	735	668
	DT + VG	869	836
	DT + ABA	679	882
Mean		854	994
Russet Burbank	IRR no AT	1290	1507
	DT no AT	741	637
	DT + VG	802	693
	DT + ABA	735	691
Mean		892	882
Mean over varieties			
IRR no AT		1041.6	1348.3
DT no AT		728.6	776.0
DT + VG		810.9	738.8
DT + ABA		760.7	811.5
CV%		21.7	19.6
p-value			
Treatment		**0.001**	**<0.001**
Variety		**0.002**	0.177
Variety × Treatment		**0.022**	0.099
Contrast *p* values			
IRR vs. DT (all)		**<0.001**	**<0.001**
DT no AT vs. DT + ATs		0.254	0.988
DT + VG vs. DT + ABA		0.037	0.417
Interaction contrast *p* values			
Variety × IRR vs. DT		**0.003**	**0.012**
Variety × DT no AT vs. DT + ATs		0.645	0.398
Variety × DT + VG vs. DT + ABA		**0.03**	0.841
SED	d.f		
Treatment	60	57.3	88.9
Variety		57.3	88.9
Variety × Treatment		114.7	177.9

3.6. Potato Physiological Disorders

This study assessed the impact of irrigation and antitranspirant treatments on key physiological disorders in Challenger and Russet Burbank potatoes at harvest and after 9 and 5 months for Exp 1 and 2, respectively. The initial data analysis revealed that Challenger was primarily susceptible to russeting, while Russet Burbank showed a greater susceptibility to jelly end rot. Tables 5–7 present the occurrence of these disorders and the number of 'disorder-free' tubers. Treatment effects were examined both pre- and post-storage to evaluate efficacy over time.

Table 5. The number and percentage of potato tubers with physiological disorders (russeting and jelly end rot) before and after storage in Experiment 1 for Challenger and Russet Burbank under different irrigation and antitranspirants. The harvested tubers were stored for 9 months for Experiment 1. Where IRR = Irrigated, DT = Drought, AT = Antitranspirant, VG = Vapor Guard, and ABA = Abscisic Acid.

Challenger	**Treatment**	**Russeting**	**Number of Disorder-Free Tubers**	**Number of Tubers Assessed**
		Experiment 1—Before Storage		
	IRR no AT	3 (20%)	12 (80%)	15
	DT no AT	11(79%)	3 (21%)	14
	DT + VG	11 (73%)	4 (27%)	15
	DT + ABA	11 (73%)	4 (27%)	15
Mean		9 (74%)	5.8 (39%)	14.8
		Experiment 1—After Storage		
	IRR no AT	12 (36%)	21 (64%)	33
	DT no AT	24 (92%)	2 (8%)	26
	DT + VG	16 (55%)	13 (45%)	29
	DT + ABA	19 (76%)	6 (24%)	25
Mean		17.8 (62%)	10.5 (37%)	28.5
Russet Burbank	Treatment	Jelly End Rot	Number of Disorder-Free Tubers	Number of Tubers Assessed
		Experiment 1—Before Storage		
	IRR no AT	1 (7%)	14 (93%)	15
	DT no AT	2 (15%)	11 (85%)	13
	DT + VG	3 (23%)	12 (92%)	13
	DT + ABA	3 (20%)	12 (80%)	15
Mean		1.5 (11%)	12.3 (88%)	14
		Experiment 1—After Storage		
	IRR no AT	2 (9%)	20 (91(%)	22
	DT no AT	9 (45%)	11 (55%)	20
	DT + VG	0	24 (100%)	24
	DT + ABA	2 (8%)	22 (92%)	24
Mean		3.3 (15%)	19.3 (86%)	22.5

The number of assessed potato tubers does not always match the sum of the number of tubers with disorders and disorder-free tubers because some tubers had multiple disorders.

In Challenger, the russeting incidence in Exp 1 was significantly reduced under irrigation compared to DT treatments (Table 7). In Exp 2, there was no significant difference between IRR and DT treatments before storage (Table 7). However, irrigation significantly reduced russeting after storage compared to drought treatments. Before storage in Exp 2, the DT + VG treatment significantly reduced the russeting incidence compared to DT + ABA, and this significant difference persisted after storage. In Russet Burbank, JER was more problematic, particularly after storage. In Exp 1, a significant reduction was observed from ATs compared with DT no AT after storage (Table 7). Exp 2 showed a significant reduction in JER after storage from irrigation (Table 7). Across all disorders studied, Challenger and Russet Burbank showed the highest percentage of disorder-free tubers in the IRR treatment (64% to 100%; Tables 5 and 6), indicating the beneficial role of irrigation in maintaining tuber quality. The effects of treatments on disorder-free tubers generally mirrored those of russeting for Challenger and JER for Russet Burbank, as seen in the 'Disorder-Free' column of Table 7. Overall, the treatment effects were more pronounced after storage for the varieties tested.

Table 6. The number and percentage of potato tubers with physiological disorders before and after storage in Experiment 2 for Challenger and Russet Burbank under different irrigation and antitranspirants. The harvested tubers were stored for 5 months. Where IRR = Irrigated, DT = Drought, AT = Antitranspirant, VG = Vapor Gard, and ABA = Abscisic Acid.

Challenger	**Treatment**	**Russeting**	**Number of Disorder-Free Tubers**	**Number of Tubers Assessed**
		Experiment 2—Before Storage		
	IRR no AT	3 (20%)	12 (80%)	15
	DT no AT	9 (64%)	5 (36%)	14
	DT + VG	2 (13%)	13 (87%)	15
	DT + ABA	10 (67%)	4 (27%)	14
Mean		6 (41%)	8.5 (57%)	14.5
		Experiment 2—After Storage		
	IRR no AT	5 (21%)	19 (79%)	24
	DT no AT	20 (95%)	1 (5%)	21
	DT + VG	3 (14%)	18 (86%)	21
	DT + ABA	23 (85%)	4 (15%)	27
Mean		13 (52%)	10.5 (44%)	23.8
Russet Burbank	Treatment	Jelly End Rot	Number of Disorder-Free Tubers	Number of Tubers Assessed
		Experiment 2—Before Storage		
	IRR no AT	0	15 (100%)	15
	DT no AT	0	13 (92%)	13
	DT + VG	0	12 (83%)	12
	DT + ABA	3 (20%)	12 (80%)	15
Mean		0.75 (5%)	13 (94%)	13.8
		Experiment 2—After Storage		
	IRR no AT	1 (4%)	23 (92%)	24
	DT no AT	5 (23%)	17 (73%)	22
	DT + VG	0	12 (100%)	12
	DT + ABA	2 (10%)	18 (80%)	20
Mean		2 (10%)	17.5 (90%)	19.5

The number of assessed potato tubers does not always match the sum of the number of tubers with disorders and disorder-free tubers, because some tubers had multiple disorders.

Table 7. p values from orthogonal comparisons of physiological disorders (russeting and jelly end rot) across two potato varieties (Challenger and Russet Burbank) before and after storage under different irrigation and antitranspirant treatments in two experiments. The harvested tubers were stored for 9 and 5 months for Experiments 1 and 2, respectively. Bold numbers indicate significant differences at $p < 0.05$. Where IRR = Irrigated, DT = Drought, AT = Antitranspirant, VG = Vapor Guard, and ABA = Abscisic Acid. Dashes (-) indicate where comparisons were not applicable, or data was unavailable.

Experiment	Storage	Variety	Comparison	Russeting	Jelly End Rot	Disorder-Free
1	Before	Challenger	IRR vs. DT (all)	**<0.001**	-	**<0.001**
			DT no AT vs. DT + ATs	1.000	-	1.000
			DT + VG vs. DT + ABA	1.000	-	1.000
1	After	Challenger	IRR vs. DT (all)	**<0.001**	-	**<0.001**
			DT no AT vs. DT + ATs	**0.013**	-	**0.013**
			DT + VG vs. DT + ABA	0.155	-	0.155
1	Before	Russet Burbank	IRR vs. DT (all)	-	0.418	0.257
			DT no AT vs. DT + ATs	-	1.000	0.696
			DT + VG vs. DT + ABA	-	1.000	0.682
1	After	Russet Burbank	IRR vs. DT (all)	-	0.726	0.348
			DT no AT vs. DT + ATs	-	**<0.001**	**<0.001**
			DT + VG vs. DT + ABA	-	0.212	**0.050**
2	Before	Challenger	IRR vs. DT (all)	0.070	-	0.070
			DT no AT vs. DT + ATs	0.203	-	0.203
			DT + VG vs. DT + ABA	**0.003**	-	**0.003**
2	After	Challenger	IRR vs. DT (all)	**<0.001**	-	**<0.001**
			DT no AT vs. DT + ATs	**<0.001**	-	**<0.001**
			DT + VG vs. DT + ABA	**<0.001**	-	**<0.001**
2	Before	Russet Burbank	IRR vs. DT	-	0.548	0.173
			DT no AT vs. DT + ATs	-	0.537	0.643
			DT + VG vs. DT + ABA	-	0.25	1.000
2	After	Russet Burbank	IRR vs. all DT (all)	-	**<0.001**	0.324
			DT no AT vs. DT + ATs	-	0.109	0.285
			DT + VG vs. DT + ABA	-	0.503	0.271

4. Discussion

This study highlights the consistent effects of water stress and antitranspirant treatments on plant water status and tuber quality. VG and ABA improved the RWC under drought conditions, though their impact on the stomatal conductance and yield varied depending on the environmental conditions and potato variety. Previous research [37] emphasised that applying ATs during critical growth stages can mitigate drought stress by maintaining plant water status, leading to improvements in yield and quality [38]. While the physiological benefits (RWC) in our study were consistent, stomatal conductance and yield outcomes remained inconsistent, likely influenced by variety-specific responses and environmental factors. Additionally, ATs reduced physiological disorders, contributing to enhanced tuber quality. The following sections explore these findings in more detail, focusing on the interactions between water stress and AT treatments and their influence on the growth, yield, and tuber quality.

4.1. Effect of Water Stress and AT Application on RWC

The relative water content is a critical indicator of a plant's water balance and ability to retain water under drought stress [39,40]. As shown in our results, DT stress significantly reduced the RWC across all potato varieties in both experiments. This aligns with previous research showing that water loss correlates with the intensity of the drought stress in potatoes [15,41] and other crops like tomatoes [16].

Antitranspirant applications significantly influenced the RWC across all potato varieties. In Exp 1, DT + VG consistently outperformed DT + ABA in improving the RWC, with significant differences observed. VG's superior performance may be attributed to its mechanical blocking of stomata and cuticular transpiration reduction, which can substantially limit water loss even when stomata are not fully closed. This aligns with findings in rapeseed and wheat, where VG and similar film-forming antitranspirants significantly improved the RWC under drought stress by increasing the leaf surface resistance to water vapour diffusion [42,43]. In Exp 2, VG increased the RWC by 44.4%, while ABA increased it by 8.2% (DT no AT vs. DT + ATs). The consistent effectiveness of VG in both experiments agrees with findings in other crops, such as wheat [17], oilseed rape [20], and strawberries [40], where film-forming ATs, such as VG, significantly increased the RWC under drought conditions. However, [18] found that VG's efficacy can vary depending on the crop type and environmental conditions.

Although the mean variety effect was not statistically significant, there were observable differences in potato variety responses to AT treatments, suggesting potential variations in drought tolerance mechanisms among varieties, which warrant further investigation into genetic or physiological factors.

Changes in the RWC likely relate to other drought response mechanisms in potatoes, such as alterations in the stomatal conductance. However, since the stomatal conductance did not decrease significantly with the AT application, the observed improvement in the RWC, particularly with VG, may be due to reduced residual transpiration, such as that occurring through the cuticle [44,45]. This supports the hypothesis that film-forming ATs can act independently of stomatal closure by forming a semi-permeable film on the leaf surface that increases the resistance to water vapour diffusion.

Interestingly, despite the substantial reduction in the RWC under drought, wilting symptoms were not always observed. One possible explanation could be related to the elasticity of cell walls in potato leaves. According to [46], an increased cell wall elasticity allows turgor to be maintained at lower RWC levels, thereby delaying the onset of wilting.

For ABA, although its effect on the RWC was less pronounced, it may operate through systemic physiological processes. ABA is known to influence root-to-shoot signalling and biomass partitioning, which can modulate the water uptake capacity and overall plant water status. While we did not measure root-to-shoot ratios in this study, such a mechanism could help explain ABA's modest impact on the RWC and aligns with its documented role in altering the biomass allocation under stress conditions [47]. VG's effectiveness in improving the RWC across potato varieties suggests it has the potential as a valuable drought mitigation tool for growers, potentially enhancing the crop resilience and yield stability under water-limited conditions. However, the variability in AT effectiveness between experiments and the potential for variety-specific responses highlight the need for further research to optimise AT use across different potato varieties and environmental conditions.

4.2. Water Stress Depressed Stomatal Conductance

Drought treatments significantly reduced the stomatal conductance. The DT plants experienced moderate/severe water stress for a prolonged period. Although the plants were watered regularly to maintain an accessible soil moisture, the soil VWC measured before watering was close to the PWP for much of the time. At ~20 days after treatment (DAT), the stomatal conductance in drought-exposed plants decreased to 134 mmol m^{-2} s^{-1}, compared to 540.2 mmol m^{-2} s^{-1} in irrigated plants. These results are consistent with those of [48], who reported significant reductions in stomatal conductance during winter wheat's jointing and heading–flowering stages under drought stress. Our study observed a 52.5% reduction in stomatal conductance across both experiments, which is comparable to the ~50% reduction reported for drought-sensitive potato varieties [49]. Other studies have found even greater reductions in certain genotypes [50]. These findings underscore the role of stomatal regulation as a key drought response mechanism, which helps conserve water but can limit photosynthesis and growth [51].

A significant time-treatment interaction was observed for stomatal conductance, reflecting the dynamic nature of plant responses to drought stress. This interaction likely results from the increasing difference in the stomatal conductance between irrigated and drought-stressed treatments as the drought severity increases. Plants typically reduce stomatal conductance to conserve water as stress intensifies. Refs. [52,53] observed that repeated drought exposure can lead to adaptive shifts in stomatal behaviour, with plants adopting more conservative water-use strategies. This adaptation can increase the stomatal sensitivity to environmental changes, persisting even after plants return to well-watered conditions.

4.3. AT Application Effects Under Water Stress on Stomatal Conductance

While antitranspirants are generally expected to reduce stomatal conductance through film formation, VG, or hormonal signalling, ABA, our results showed increased g_s in some treatments, particularly with VG. Although unlikely, since the stomatal conductance was measured long after the antitranspirant application, it might be speculated that this unexpected response could possibly reflect (1) the temporary effects of foliar spraying creating localised humidity, (2) the delayed ABA action requiring time for cellular uptake and signalling, or (3) VG's film properties initially trapping moisture around the stomata before reducing transpiration.

Antitranspirant-treated plants exhibited a significant improvement in stomatal conductance compared to untreated drought-stressed plants in Exp 1, aligning with studies showing the AT efficacy under severe drought in wheat [17]. However, in Exp 2, ATs did not significantly alter stomatal conductance compared to drought alone. The limited stomatal response to antitranspirants in our study may also relate to potato's inherent isohydric behaviour, where stomata close early during soil drying to maintain the leaf water potential [54]. In isohydric species like potato, endogenous ABA levels may already be elevated under drought, potentially limiting the additional effects of exogenous ABA applications and the potential for reduced transpiration from VG applications. Varietal responses to AT treatments were consistent across varieties for all variety-related interactions, with no variety-specific differences in stomatal conductance, contrasting with other work [30], which reported significant variety-specific reductions in stomatal conductance under drought, suggesting that ATS may standardise responses across varieties under acute stress. The observed varietal inconsistency, particularly Challenger's poor response to ABA, suggests genetic differences in ABA sensitivity that warrant further investigation [55], indicating that the antitranspirant efficacy may depend more on the environmental stress severity than on stomatal regulation mechanisms.

Our results suggest a complex interaction between ATs and plant water relations. While ATs generally reduce stomatal conductance, the extent of this reduction may depend on various factors, including the variety, drought level, and environmental conditions. For instance, one study [17] found that VG (di-1-p-menthene) significantly reduced stomatal conductance under progressive drought but induced a nonsignificant increase under mild controlled drought in wheat.

The improved stomatal conductance in AT-treated plants observed during severe drought (Exp 1) in our study might be attributed to improved water retention and reduced water stress, allowing the stomata to remain open longer than they would under drought stress alone. This supports other work [56] where partial stomatal closure sustained photosynthesis. Conversely, under milder stress (Exp 2), ATs failed to enhance stomatal conductance, echoing another study [17], which reported nonsignificant AT effects under moderate drought in wheat. This suggests that AT efficacy is context-dependent, hinging on the drought severity and growth stage.

These findings suggest that ATs can mitigate water loss without inducing full stomatal closure, potentially supporting continued photosynthesis during moderate water stress. However, the variability in responses highlights the need for further research to understand and optimise AT application strategies based on the drought intensity and varietal physiological traits.

4.4. Effect of Water Stress and AT Application on Potato Yield

Persistent water stress during tuber formation and expansion reduces potato yields [39,57]. Drought conditions adversely affect the RWC, leaf gas exchange, and the efficient partitioning of assimilates, which are crucial for tuber development. This stress leads to declines in the tuber size, number, and yield. Specifically, water shortages during critical growth stages, particularly tuberization and bulking, hinder the translocation of carbohydrates to the tubers [49,58].

The irrigation treatment demonstrated significant effects on yield, with *p*-values indicating a strong impact across both experiments. This underscores the critical role of an adequate water supply in enhancing potato yields, serving as a benchmark against which other treatments, such as ATs, can be compared. Examining varietal responses, Russet Burbank experienced the highest yield reductions of 43% in Exp 1 and 58% in Exp 2, confirming its sensitivity to water stress [59]. In contrast, the Challenger variety demonstrated a better resilience, with yield reductions of 20% in Exp 1 and 27% in Exp 2. Markies, a late-maturing variety, exhibited the least yield loss at 15% in Exp 2, supporting its noted drought tolerance [41]. The timing and severity of the drought had a substantial impact on the tuber yield. Ref. [60] observed that early-season drought from emergence to tuber initiation reduced the fresh tuber weight in both early-maturing and late-maturing varieties. However, late drought during the bulking stage severely affected early-maturing varieties. Markies's resilience, therefore, may be attributed to its extended growing season, allowing greater recovery after drought stress and thereby enhancing its yield performance.

Our study revealed variability in the effectiveness of VG and ABA treatments across different varieties and conditions. In Exp 1, DT + VG reduced the yield loss by approximately 11.3% compared to untreated drought-stressed plants. However, in Exp 2, ATs had no significant effects on yield. The DT + ABA treatment reduced the yield loss in the Challenger variety by approximately 30% compared to untreated DT plants in Exp 1, with a similar but nonsignificant increase observed in Exp 2. These findings align with previous studies where ABA treatments have been shown to enhance crop yields under drought conditions. For example, an exogenous ABA application in wheat improved the shoot dry weight and maintained higher photosynthetic pigment concentrations, leading to a yield increase [19]. This suggests that ABA's role in improving the drought resilience and yield-related traits could benefit different crops, including potatoes, by optimising resource allocation and maintaining physiological functions under stress conditions. While stomatal closure was not observed in our study, ABA's effect may instead be mediated through an enhanced root-to-shoot allocation or hormonal signalling pathways that support tuber development under drought stress [47]. A significant interaction between the variety and treatment was observed in Exp 1, suggesting that variety-specific traits like the root system efficiency, biomass partitioning, and delayed tuberization confer advantages under stress conditions. However, this interaction was not significant in Exp 2. This variability underscores the importance of considering both genetic and environmental factors when evaluating the effectiveness of drought mitigation strategies in potato cultivation.

4.5. Effect of Water Stress and AT Application on Physiological Disorders

The drought stress significantly exacerbated physiological disorders such as JER and russeting compared to irrigated plants in both experiments. This is consistent with previous studies showing that water stress during tuber formation impairs water relations and increases physiological disorders [59,61,62]. In Exp 1, russeting was notably prevalent in Challenger, affecting 73–79% of drought-stressed tubers compared to 20% of irrigated tubers. This trend persisted and became worse after storage, with 92% of drought-stressed tubers affected compared to 36% of irrigated tubers. Prolonged drought stress likely led to the buildup of phellem layers, which cracked during tuber expansion, resulting in russeting [7–9], and the less severe stress in plants treated with antitranspirants may explain the reduction in russeting.

In Russet Burbank, JER was more problematic, particularly after storage. DT no AT resulted in a 45% JER incidence compared to 9% in irrigated tubers. JER is linked to the accumulation of reducing sugars (glucose and fructose) under drought stress [63], which is more prevalent in long-shaped tubers like Russet Burbank [64].

Varietal differences were significant across experiments, emphasising that different varieties have varying resistance levels to physiological disorders, influenced by their water retention capacity and drought response [39,65]. Post-storage effects were particularly notable, with treatment differences often becoming more pronounced after storage, especially for Challenger. This underscores the importance of considering both the immediate and long-term effects of drought and antitranspirant treatments on the tuber quality.

Antitranspirants showed varying efficacy in mitigating physiological disorders. In Exp 1, ATs were particularly effective for pre-storage disorders, significantly reducing russeting in the Challenger variety from 92% (DT no AT) to 55% (DT + VG). In contrast, Exp 2 showed that ATs were highly effective for post-storage disorders, reducing russeting in Challenger from 64% (DT no AT) to 13% (DT + VG). Additionally, the ABA application was effective in reducing JER in Russet Burbank after storage in Exp 1, which is consistent with research on ABA's role in managing the internal water balance under drought stress [17]. ABA likely maintained the tuber water content by regulating water fluxes and promoting protective mechanisms, like suberisation and wax accumulation, which prevent desiccation [62]. These mechanisms likely contributed to the observed reduction in the JER incidence in our study, as maintaining the tuber water content and internal osmotic balance is crucial for preventing physiological disorders during storage.

Drought stress can exacerbate physiological disorders in potato tubers, but antitranspirant treatments may help mitigate these effects. In our study, the effectiveness of VG and ABA in mitigating physiological disorders varied by the variety, specific disorder, and storage condition. Therefore, this research emphasises the importance of precise water management and the potential benefits of antitranspirant applications in minimising drought-induced physiological disorders. The findings highlight the need for further research on tailored approaches considering variety-specific responses and post-harvest storage effects to maintain the yield quality and quantity under water stress conditions [39,59].

5. Conclusions

This study demonstrates that antitranspirant treatments, particularly VG, can help maintain a higher RWC and tuber quality in potatoes under drought conditions, enhancing the plants' resilience to water scarcity. However, their impact on yield was less consistent. While VG and ABA moderately reduced the yield loss in some cases, they did not consistently improve yields across experiments. The effects of antitranspirants on physiological disorders vary by the variety, specific disorder, and storage conditions. While effective in reducing jelly end rot in Russet Burbank, their impact was not consistent across both experiments. The russeting in Challenger after storage was, however, consistently reduced by antitranspirants in both experiments. These findings emphasise the need for further research on targeted approaches in managing the tuber quality under drought stress.

Author Contributions: O.F.O.-O. was involved in methodology, formal analysis, investigation, writing—original draft, writing—review and editing, visualisation, funding acquisition; A.F. was involved in methodology, writing—review and editing, supervision; J.M. was involved in methodology, writing—review, supervision; P.K. was involved in conceptualisation, methodology, formal analysis, writing—review and editing, supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by a Commonwealth Scholarship (NGCS-2022-713) awarded to Olu-Olusegun Oluwatoyin Favour with additional funding from Harper Adams University.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Acknowledgments: The authors appreciate the advice and assistance from HAU staff: Matt Back, Sarah Cochrane, Alice Rogers, and Gary Weston. We extend our gratitude to the staff of the four seed companies that provided the tuber seed: Gavins Towers of Agrico, Louise Greenhill of IPM Potato Group, John Limmer of HZPC, and Ross Colin of McCain, and to Tom Eyles of Produce Solutions for assisting with commercial storage of harvested tubers.

Conflicts of Interest: The authors declare no conflicts of interest.

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