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Review

The Role of Antitranspirants in Mitigating Drought Stress in Plants of the Grass Family (*Poaceae*)—A Review

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Abstract: One of the biggest problems facing agriculture is the occurrence of droughts. Due to ongoing climate change, many regions of the world are exposed to increasingly frequent and prolonged water shortages. The situation may significantly reduce production and the quality of many crops in the *Poaceae* family, including crucial cereals. Therefore, it is important to find solutions that can help adapt plants to the drought phenomenon and reduce its negative effects. One measure that could potentially improve the condition of plants and help them survive under water deficit conditions is the use of antitranspirants (AT), which are products that reduce transpiration. Antitranspirants are divided into three groups: film-forming, metabolic, and reflective types. This review aimed to the current state of knowledge on the effects of selected AT applications on *Poaceae* plants under drought conditions. It demonstrated that AT, in many cases, mitigates the negative effects of drought on crops such as maize, wheat, or rice, which are crucial for global food security. Furthermore, AT often improved growth and yield parameters. These results are particularly relevant for countries that are important cereals producers and are more vulnerable to droughts in the future. However, it should be noted that the results obtained often depend on several factors, such as plant species, environment, type of antitranspirant, and applied dose. Therefore, it is advisable to measure further the effects of AT on plants under drought-stress conditions.

Keywords: antitranspirants; drought stress; cereals; *Poaceae*; grasses; crops adaptation; water deficit; Vapor Gard; chitosan; kaolin

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1. Introduction

The *Poaceae* family, also known as the grass family, includes the world's most important cereal crops. It has several key species that are the primary food source for humans. The *Poaceae* include, among others: maize (*Zea mays* L.), rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare*), sorghum (*Sorghum bicolor* L.), proso millet (*Panicum miliaceum* L.), oats (*Avena sativa*), rye (*Secale graine* L.), and triticale (*xTriticosecale*). In addition to cereals, the *Poaceae* family also includes sugarcane (*Saccharum officinarum* L.), bamboo (*Bambusa Shreb.*), and pasture grasses. Moreover, switchgrass (*Panicum virgatum* L.) or giant miscanthus (*Miscanthus giganteus*) are increasingly important, as they can be used as biofuel [1]. According to the latest phylogenetic classification, the *Poaceae* family includes 12 subfamilies comprising a total of 11,783 species [2]. Scientists claim that the grass family is one of the most important groups in the world from an economic point of view [3,4]. Unfortunately, due to climate change, species in the *Poaceae* family, like many other plants, are subject to factors that can significantly reduce the area of land suitable for cultivating these crops.

One of the factors significantly impacting and limiting crop production is the occurrence of different environmental stress factors, which can be divided into two groups: biotic and abiotic stresses. Biotic stress factors include a variety of organisms such as fungi, bacteria, nematodes, insects, herbivores, and viruses. These agents cause diseases, infections, and plant damage [5]. A side effect of the occurrence of biotic stressors is reductions in yield. On the other hand, abiotic stresses are caused by non-living natural elements, such as temperature (both too high and too low), drought, flooding, radiation, salinity, and lack or excess of minerals or heavy metals [6,7]. The severity of abiotic stresses is linked to ongoing climate change. Some regions of the world have recently experienced previously unprecedented temperature extremes. This is causing many crops to be exposed to conditions where the temperature deviates from the optimum for those species.

Moreover, extreme weather events in many regions contribute to increasing droughts and water shortages. Forecasts show that half of the global urban population are projected to live in a water-scarce region by 2050 [8]. Water shortages will also have a strong impact on crops. Therefore, it is crucial to have sustainable irrigation in water-scare regions. The appropriate irrigation scheduling can increase water productivity (i.e., product yield per unit volume of water consumed by the crop) [9]. Climate change strongly influences the irrigation water needs (IWN) through rainfall, temperature, air humidity, and the evapotranspiration of plants. Scientists predict that, up to the 2055 year, reference evapotranspiration (ETo; a sum of evaporation from the soil and transpiration from a reference crop such as, e.g., grass or alfalfa) will increase. This prediction will make the water need for irrigation even higher [10]. Considering, that the world's water resources are limited, an extremely important goal is to find solutions to improve plant productivity in drought conditions. Solutions that extend the geographical boundaries of drought-resistant production and are not solely based on additional irrigation are needed. One of the promising solutions may be the use of antitranspirants [11].

Antitranspirants (AT) are products that reduce transpiration from the above-ground parts of the plants. The basic division of AT comprises three groups: film-forming, metabolic (stomata-closing), and reflective type (Figure 1). The first group includes film-forming antitranspirants. After their application to the plant, a physical barrier (film) is formed over the stomata, thus reducing transpirational water loss. This group mainly includes water-emulsifiable organic polymers, latex, plastics, or wax emulsions [12]. A popular commercial formulation in this group is Vapor Gard® (Bio Agris brand)—a water-emulsifiable organic concentrate composed of di-1-p-menthene ($C_{20}H_{34}$). This terpene polymer also functions under the name of pinolene, which is produced from conifer resins during distillation [13]. The second group is metabolic AT, otherwise known as stomata-closing preparations. Applying this type of AT causes partial stomatal closure, which results in lower transpiration. This group includes substances with hormonal and hormone-like effects [14]. The most common metabolic AT include chitosan, fulvic acid, and abscisic acid (ABA). The last group of antitranspirants is the reflective type, which contributes to increased reflectance and a concomitant reduction in leaf temperature and transpiration rate [14–16]. One of the most popular AT in this group is aluminum phyllosilicate $Al_2Si_2O_5(OH)_4$—also known as kaolin [17]. According to a literature review by Mphande et al. [14], kaolin was the most studied reflective antitranspirant on arable crops from 2009 to 2018. Other preparations included in this group are calcium carbonate ($CaCO_3$) and calcium oxide (CaO), which have similar properties.

The aim of this study was to review and present the effects (mainly on yield and plant growth parameters) of using the popular antitranspirants on *Poaceae* crops under drought stress conditions. The antitranspirants selected for this study included: Vapor Gard, silicon, chitosan, fulvic acid (FA), salicylic acid (SA), kaolin, and magnesium carbonate ($MgCO_3$). The review is based on publications no older than 2000 available in Web of Science and Google Scholar databases. The main objective of this work was to synthesize results obtained to date on the potential effects of antitranspirants in drought mitigation in plants of the *Poaceae* family.

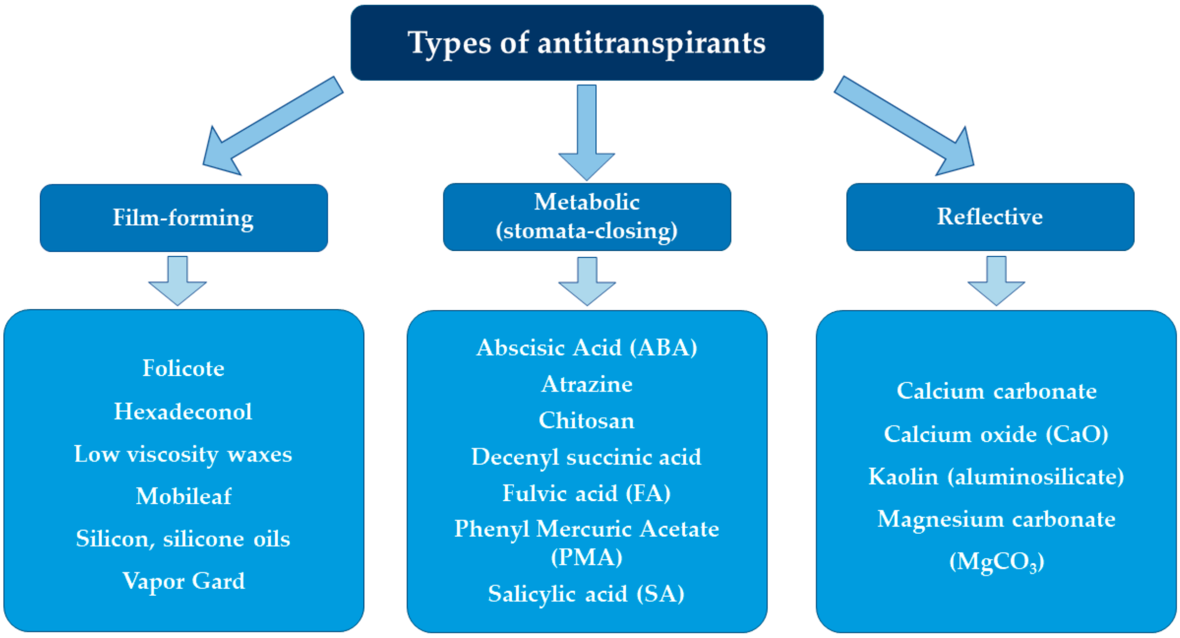

Figure 1. Groups of antitranspirants and their examples based on [14,16,18,19].

2. Drought

One of the most likely climate changes is the occurrence of extreme heat waves and prolonged periods of drought, which significantly impact crop production. The World Health Organization (WHO) defines drought as a prolonged dry period in the natural climate cycle that can occur anywhere in the world. It is a slow-onset disaster characterized by a lack of precipitation, resulting in a water shortage [20]. Long-term water shortages result in reduced plant growth, leaf area, fruit weight, and yield. It is crucial to conduct research to understand better this stress's impact on plants and their adaptation strategies to periods of water deficits [21]. The drought tolerance mechanism is a complex issue that has been the subject of many studies. It involves a lot of physiological and biochemical processes at the cell, tissue, organ, and whole-plant level. Moreover, the duration of the drought, its severity, the term of occurrence, and the rate of development directly impact the plants' response to water deficit [22]. Researchers note that the impact of drought stress can be reduced by applying appropriate agricultural operations. These treatments include seed priming, setting planting and harvesting dates, the application of plant growth regulators, modification of tillage methods such as conservation tillage, and the timely management of weeds. In addition, there is great potential in developing breeding and biotechnology research. This research focuses on producing crop varieties that are tolerant and resistant to drought stress. So far, cultivating resistant varieties has contributed to higher yields under drought conditions and thus can enhance global food security [23]. The researchers emphasize that it is extremely important to include drought-tolerant varieties in national climate change adaptation plans [24]. Among all these ways of alleviating drought stress in plants, using antitranspirants could also be a potential solution. This is due to the fact that the main role of these substances is to reduce transpiration, which should positively affect the ability of the plants to adapt to long periods without water. This fact makes research on applying antitranspirants on plants belonging to the *Poaceae* family increasingly popular.

Both drought and the application of antitranspirants can affect plant parameters such as morphological, physiological, biochemical, yield, and yield components (Figure 2). The morphological ones include elements such as leaf area, number of leaves, plant height, stem width, stem length, as well as other species-specific growth characteristics that can be inhibited under drought. Furthermore, one of the main plant responses to this stress is stomatal closure, which reduces photosynthesis [25]. Changes in photosynthesis are categorized as physiological response. Besides this, it also includes relative water content

(RWC), leaf water potential, stomatal conductance, CO_2 assimilation and transpiration rate, among others. In addition, an important aspect concerning drought is also the plant response, which includes biochemical aspects such as, for example, antioxidant enzyme activity and chlorophyll content. However, from the farmers' point of view, one of the most important groups of parameters affected by drought is the last one comprising yield and its parameters. Elements such as plant dry weight, seed yield, harvest index, number of seeds per spike, and 1000 seed weight, among others, directly affect a crop's productivity and financial return.

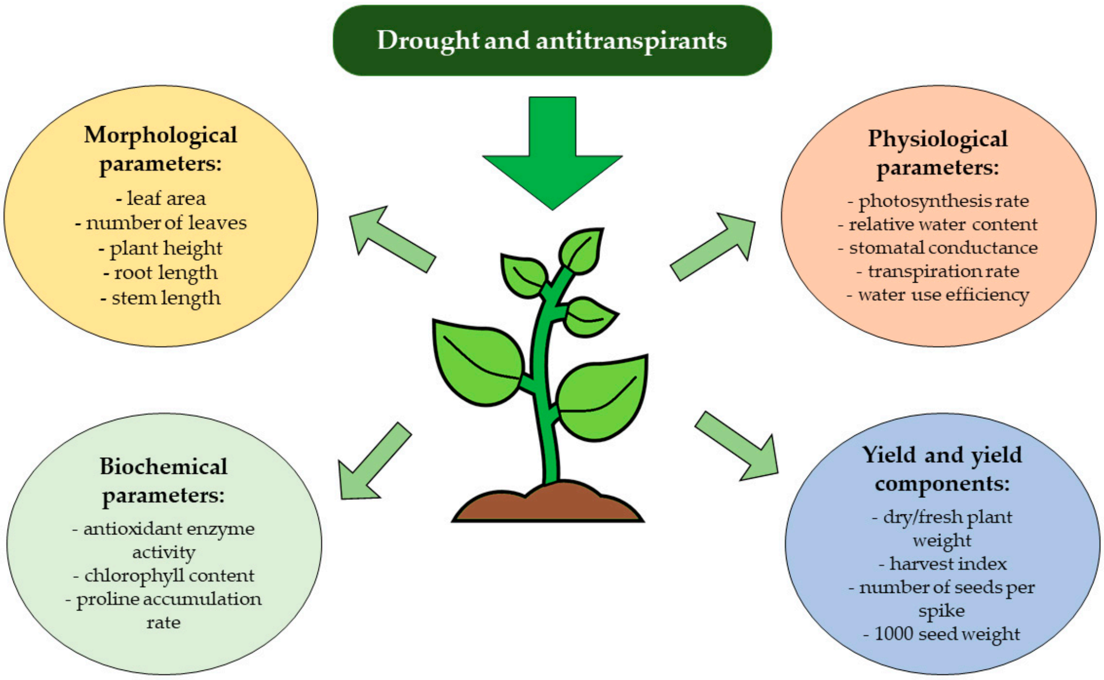

Figure 2. Examples of the effects of drought and antitranspirants on plant parameters.

3. Film-Forming Antitranspirants

3.1. Vapor Gard

One of the most widely used film-forming antitranspirants is Vapor Gard. Its formulation is based on polymer di-1-p-menthene (pinolene). According to Abdullah et al. [26], on wheat under drought, it was seen that plants treated with Vapor Gard used, on average, 45% less water than those untreated. Furthermore, under drought conditions, wheat with antitranspirant received higher grains per spike and more yield than without its use [26]. This is also confirmed by a later study, in which the application of Vapor Gard contributed to a significant increase in spring wheat yield (0.7–1.09 $Mg \cdot ha^{-1}$) under drought conditions. The treatment reduced drought-induced losses in the number of grains per square meter by an average of 13% [27]. Another study using di-1-p-menthene showed that yield decreased, but only when Vapor Gard was applied during the development stage from inflorescence emergence to anthesis. When it was treated before the most drought-sensitive stage (at the flag leaf stage), an improvement in yield was observed [28]. Moreover, research on winter wheat showed that an AT (di-1-p-menthene) applied under water deficit conditions affected yields by reducing grain losses caused by drought [29]. A study by Ouerghi et al. [30] showed that Vapor Gard under water deficit conditions increased leaf water potential in durum wheat and barley. However, at the same time, it was shown that using this antitranspirant at concentrations of 5, 7, and 10% did not reduce the negative effects of water stress on the photosynthetic rate. It was also found that Vapor Gard reduced water deficit, but only for a short time. Other measurements on wheat have demonstrated that, despite a reduction in photosynthesis, higher yields can be obtained when this antitranspirant is applied before the meiosis phase (which is drought-sensitive). This increase has been associated with improved pollen viability [31]. Additionally, an experiment on another plant in this family (maize) showed the positive effect of Vapor Gard on plant height and the number of leaves under water deficit conditions. Furthermore, an improvement in the leaf area index and also in the amount of plant dry matter was observed [32].

Table 1 shows research published since 2000 on the application of Vapor Gard on plants of the *Poaceae* family concerning drought stress. It can be seen that, among all plants, wheat was the dominant one on which experiments were most often conducted. The researchers mainly focused on evaluating aspects related to yield and its parameters. It is noteworthy that there is little research concerning the other plants. This overview shows that the number of experiments concerning the application of Vapor Gard and its effects on drought stress levelling on plants of the *Poaceae* family should be significantly increased. This is particularly relevant for plants that are key for human food security, such as rice and maize.

3.2. Silicon

A few articles also include silicon (Si) or silicone oils as antitranspirants [18,19,33]. However, in their review of antitranspirants, Mphande et al. [14] omitted silicon, arguing that, while it does have a drought-mitigating effect, it is not directly related to transpiration. During experiments conducted on maize, Gao et al. [34] observed that silicon significantly decreased transpiration rate and conductance for both adaxial and abaxial leaf surface [34]. It has also been noted that wheat leaves treated with Si under drought conditions are thicker, which may have the effect of reducing transpirational loss of water [35]. However, there are also studies in which different results were obtained. Measurements on rice showed that applying Si significantly increased the photosynthetic and transpiration rates under drought conditions [36]. Additionally, in wheat, Si under drought conditions contributed to an increase in net photosynthetic rate and transpiration rate, but regarding controls without this stress, no effect of Si on these parameters was observed [37]. Moreover, Gong and Chen [38] showed that silicon can improve photosynthetic ability and increase the leaf net photosynthetic rate in wheat under drought conditions. Rizwan et al. [39] in their review, state that the differential effect of silicon on transpiration is due to the dose applied and the crop type. They also point out that there is still a need for more detailed studies that will provide a better understanding of the effects of Si on gas exchange under drought stress conditions.

Numerous studies highlight that silicon is generally recognized as an element that alleviates plant drought stress [40–42]. However, researchers point out that the effect of its application in many cases is not clear-cut and depends on differences between species, genotypes, and also environmental conditions [43]. It has been observed that Si application increases dry maize matter but only under water deficit conditions. For well-watered plants, no significant differences were observed after the application of Si. Parveen et al. [44] also noted a positive effect on dry matter and showed that seed priming with Si in maize contributes to improving shoot and root lengths as well as their biomass [44]. Moreover, Si priming at a concentration of 0.006 mol·L^{-1} increased the chlorophyll content of the corn crop by 74% under drought stress conditions and by 55% under non-stress conditions [44]. The researchers emphasize that, despite the positive effect of Si on increasing chlorophyll levels under water deficit conditions, a value equal to plants under well-watered conditions was not achieved [45]. In the case of maize, silicon was also found to improve physiological performance, water use efficiency, and productivity under drought stress conditions [46]. Moreover, it has been observed that Si-applied corn shows a higher relative water content (RWC), water potential, and leaf area than untreated corn [35]. On the other hand, Kaya et al. [45] noted that RWC increased with silicon application but only under water deficit conditions. No significant differences were found in well-watered maize.

Improvements in RWC under drought conditions were also observed in wheat [38]. In their study, Gong et al. [47] also observed a correlation that Si use increased the water potential of drought-affected wheat plants at the filling stage but not at the booting stage. The application of silicon in wheat can also influence higher plant growth than those without Si [37]. In the case of sorghum, it was observed that Si application enhanced water uptake ability [48]. In addition, Si was found to reduce the negative effects of drought on dry matter decline in this crop. Interestingly, its beneficial effect was seen only under this stress, while under wet conditions, no effect of Si on this parameter was noticed [48]. Analogous results were obtained for rice, where Si had no effect on dry weight under wet conditions, but during drought stress, a definite improvement in this parameter was observed [36]. Another experiment on rice showed that Si significantly affected plant height growth, rice straw, root yield, and grain yield under reduced soil moisture conditions. It was found that silicon could reduce the water supplied to rice by 30% and maintain straw and grain yield at the same level as under full irrigation [49].

Table 1 shows the studies carried out on the application of silicon concerning drought on plants of the *Poaceae* family. It can be seen that, with the use of this AT, the researchers' interest in each group of parameters was similar, and they investigated morphological, physiological, and biochemical parameters as well as yield and yield components. Furthermore, it can be observed that research with silicon is more popular than with Vapor Gard.

Table 1. Examples of studies on using film-forming antitranspirants (Vapor Gard and silicon) concerning drought stress on *Poaceae* plants.

	Morphological Parameters		**Physiological Parameters**		**Biochemical Parameters**		**Yield and Yield Components**	
	Vapor Gard (di-1-p-Menthene)	**Silicon**	**Vapor Gard (di-1-p-Menthene)**	**Silicon**	**Vapor Gard (di-1-p-Menthene)**	**Silicon**	**Vapor Gard (di-1-p-Menthene)**	**Silicon**
Barley			[30]					
Forage grasses		[50]		[50]		[50]		[50]
Maize	[32]	[44,46,51]		[34,45,46,51,52]		[44–46,51]	[32]	[45,46,52]
Pearl millet		[53]				[53]		[53]
Rice		[36,49]		[36,49]		[36]		[36,49]
Sorghum		[48]		[48]				[48]
Sugarcane						[54]		
Wheat		[35,37,55]	[26,29,30,56]	[35,37,38,55,57]	[27,56]	[37,38,47,55,57]		[35,37,55]

4. Metabolic (Stomata-Closing) Antitranspirants

4.1. Chitosan

Scientists are increasingly studying the effects of chitosan on plants. In recent years, there has been a rapid growth in the number of published articles on its use on cereals [58]. This is because chitosan is one of the more widespread representatives from the metabolic (stomata-closing) antitranspirants group. Chitosan is a biopolymer derived from chitin. It is non-toxic, biodegradable, and often used as a crop biostimulant [59]. Researchers have noted the potential of chitosan for use on maize to increase water stress tolerance [60]. Measurements carried out under water deficit stress showed that using chitosan on maize increased the content of chlorophyll a, chlorophyll b, and relative water content. Under these conditions, there has also been a significant improvement in shoot length, shoot fresh and dry weights, root length, as well as root dry and fresh weights [52]. Similarly, in the case of wheat, a significant increase in germination rate, wet weight, root length, and root activity was observed after coating with chitosan [61]. Furthermore, it has been demonstrated that chitosan can partially mitigate the effects of drought on wheat, mainly by improving plant growth and development and consequently increasing yield [62]. Moreover, research on wheat under limited irrigation conditions showed an economical yield improvement after using chitosan. The beneficial effect was increased when it was applied together with hydrogel [63]. The exogenous use of chitosan has been demonstrated to improve many diverse parameters such as increases in chlorophyll content, carotenoid, yield parameters, flag leaf area, shoot dry weight, and water use efficiency (WUE) [56]. Moreover, other studies have shown that after the application of chitosan, parameters such as plant height, number of tillers per hill, flag leaf length, and flag leaf width increased compared to the control sample in water deficit. There was also a slight improvement in yield indices such as biological yield, grain yield, and harvest index. However, results exceeding the parameters under normal conditions (without drought) were not achieved [64]. Similar results to those reported by Burondkar et al. [64] were also obtained with chlorophyll and relative water content (RWC) by Singh et al. [65]. Other studies on wheat under drought conditions have shown that applying chitosan nanoparticles also increases grain yield. The highest value was obtained using the highest concentration of this agent tested (90 $\mu mol \cdot mol^{-1}$). It also tested whether the application method influenced AT's effectiveness. However, in this case, no significant differences were found between foliar and the soil-based application of chitosan [66].

Moolphuerk and Pattanagul [67] showed that, under drought conditions, rice treated with chitosan increased chlorophyll a, chlorophyll b, and water content. The improvement in these parameters is promising in the context of climate change. Furthermore, studies on rice have identified that chitosan induces drought resistance [68]. A significant increase in yield and its components was also observed. It is related to the fact that rice produces metabolites that close the stoma and, as a result, transpiration is reduced and plants use less water. This process helps them to survive the drought [69]. Nevertheless, through using chitosan and pusa hydrogel simultaneously under water deficit conditions, higher growth and yield parameters and RWC were achieved compared to the non-use of antitranspirants under normal conditions [64].

In a study of the chitosan application to pearl millet, drought was enforced by stopping irrigation during the flowering period. A reduction in stomatal conductance and limitation in transpiration were observed in the treated samples. Additionally, the use of chitosan caused higher leaf water status under these conditions than in unsprayed plants. Furthermore, 1000 grain weight and grain yield increased [70]. Research has also been conducted on creeping bentgrass (*Agrostis stolonifera* L.). It was recorded that chitosan could significantly improve drought tolerance in these plants. This has been confirmed by study results that show physiological changes, including higher RWC, cell membrane stability, and photosynthesis. Furthermore, under these conditions, chitosan promoted WUE and carbohydrate production [71]. The increases in all relevant parameters compared to the control plants, also under drought conditions, allows concluding that chitosan has the great potential to reduce the negative effects of drought. The tendency of chitosan nanoparticles to reduce the effects of drought stress was also demonstrated in barley. A significant increase in RWC, the 1000-grain weight, and grain protein was observed after its use [72]. Additionally, it has been reported that chitosan improves RWC, chlorophyll a and b, and barley growth parameters under reduced irrigation [73].

Research conducted to date on the *Poaceae* family has included not only the use of chitosan but also its derivatives, such as N-succinyl chitosan and N, O-dicarboxymethylated chitosan. Their application on maize contributes to the plant's tolerance to water stress [74]. Measurements carried out on maize hybrids after the use of chitosan showed that it affected the anatomy of the roots. Moreover, this change directly increases the adaptation of the plant to a period of stress [75]. The timing of AT application was also an interesting issue considered by the researchers. Studies of different dates of chitosan application (before, during, and after a drought) show that the best results were recorded when it was used before the drought. Extensive scientific research and the results discussed above indicate that chitosan can be considered as an effective tool for increasing plant resistance to drought.

The summary of the studies on applying this antitranspirant to drought (Table 2) shows that they were carried out on many aspects of both physiological, biochemical and yield parameters of plants from the *Poaceae* family. Experiments were performed on crops such as wheat, maize, rice, barley, sorghum, pearl millet, bermudagrass, or creeping bentgrass. Previous analyses show that scientific interest in this antitranspirant has increased significantly since 2000 [50]. Therefore, there is a chance that even more knowledge will soon become available for this agent, allowing it to be used more effectively.

4.2. Fulvic Acid (FA)

In studies conducted under drought condition, an increase in the water content of leaves was observed after the application of fulvic acid on winter wheat [76]. This result may lead to the conclusion that this metabolic-type antitranspirant can be an appropriate proxy in minimizing the negative effects of drought. As proof, a study in which soil was mixed with fulvic acid before having wheat grown on it under water stress conditions can be cited. These experiments showed that treatment with AT resulted in greater plant height and root length than plants from untreated soil [77]. Favorable results were also obtained with the maize treatment. CO_2 assimilation, photosynthesis, transpiration rate, and water-use efficiency were increased. Additionally, growth indicators such as the number of leaves, cob length, and fresh and dry weight were improved. Yield, biological yield, grain yield, and harvest index also increased [78]. It was also shown that this AT increased drought tolerance by affecting maize shoot growth and leaf physiology [79]. In a study conducted by Yang et al. [80], a non-significant increase in yield was noted after FA application under drought conditions on maize. Nevertheless, the application of this substrate in combination with a superabsorbent polymer (SAP) significantly increased yield and the number of grains by 19.1% and 23.1%, respectively [81]. A similar result was obtained regarding water use efficiency at the grain yield level of maize under water deficit conditions. FA treatment alone did not cause a significant effect, but together with SAP, contributed to an improvement of 25.3%. Yang et al. [80] suggested that a combination of SAP and FA could be particularly valuable in dry regions of the world.

During the current review, not many articles were found referring to the application of this AT on plants of the *Poaceae* family in the context of drought, as can be seen in Table 2. Therefore, it is important to continue research on the application of this antitranspirant in order to get a complete picture of its impact.

4.3. Salicylic Acid (SA)

Salicylic Acid is classified as a plant growth regulator substance and as an antitranspirant belonging to the metabolic group. Salicylic Acid (SA) is widely used in *Poaceae* crops. Research has been conducted with respect to its use on many crops such as corn, wheat, sorghum, and barley. Under drought conditions, studies of the application of SA on barley have shown that it improves parameters such as relative water content, nutrient contents, and proline accumulation [82]. In addition, an increase in RWC, dry mass improvements, photosynthesis, and net CO_2 assimilation rate was noted with the use of salicylic acid [83]. While conducting other research on the usage of SA, Fayez and Bazaid [84] noted improvements in chlorophyll a and b content, as well as the fresh weight of barley shoots under drought conditions. Additionally, the pre-treatment of barley in the early growth stage with this substance reduces the leaf cell membrane damage caused by water deficit [85]. A positive effect was also noted in the case of rice. As a result, an enhancement in plant height as well as seedling fresh and dry weight was observed [86]. Furthermore, parameters such as fresh and dry weight, RWC, leaf CO_2 net assimilation rate, a-amylase activity, and soluble sugars increased. Moreover, Farooq et al. [86] indicated that the method used to apply SA has an impact on the obtained results, as they showed that foliar application is more effective than seed treatment.

A positive effect was also observed in wheat (cv HD-2329), where plants treated with SA significantly increased dry weight, leaf chlorophyll, and moisture content [87]. Additionally, a subsequent study on two wheat varieties (drought susceptible—Basribey 95 and drought resistant—Ziyabey 98) showed that SA reduces the negative effects of drought. Improvements in parameters such as grains per spike, RWC and chlorophyll content, and antioxidant enzyme activity were observed [88]. In the case of the Zarrin wheat cultivar, improved growth and yield indices were observed when salicylic acid was applied. The plant height, number of tillers per square meter, grains number per spike, 1000 seed weight, and harvest index increased. This shows the drought-alleviating effect of SA [89]. The application of 0.0005 mol·L^{-1} of SA also had a significantly positive effect on wheat height and dry and fresh weight for the 'Yumai 34′ cultivar. Furthermore, a decline in the influence of drought was confirmed by the fact that the absolute water content improved [90]. In Roshan and Mahdavi wheat varieties, using SA mitigated the negative effects of drought stress and improved the vigor index [91]. An enhancement of the stomatal conductance of wheat was also obtained after using salicylic acid. However, a result equivalent to drought-free conditions was not achieved [92]. Nevertheless, the mitigating effect of salicylic acid on drought stress in wheat has been confirmed in several studies [93–96].

Another plant from the *Poaceae* family on which research is being conducted is sorghum. The frequency of this research is related to the fact that the main producers of this cereal are African countries, which, due to their location, often face problems related to water availability. In the case of this species, the application of AT has an alleviating effect against this stress [97]. Under drought conditions, plants treated with SA showed improvements in shoot length, fresh weight, and dry weight values compared to plants that were not treated with SA [98]. Furthermore, an improvement in emergence percentage and rate, chlorophyll b, and protein content was also observed in sorghum [99].

Studies conducted on maize under drought conditions occurring at the 10–12 leaf stage also showed a positive effect of salicylic acid. By applying SA, a significant increase in parameters such as plant height, ears height, length, leaf area, kernel row no per ear as well as per row were observed compared to plants without SA treatment [100]. For maize, foliar application of 100 µmol·mol^{-1} SA was also shown to increase chlorophyll and potassium content, RWC, and leaf membrane stability index under drought conditions. Interestingly, at a higher SA concentration (of 200 µmol·mol^{-1}), a decrease in all of the above parameters, except potassium content, was obtained [101]. The more favorable effect of smaller doses of salicylic acid on growth parameters was also confirmed by Manzoor et al. [102]. Their results show that among the concentrations of 0.005, 0.01, and 0.015 mol·L^{-1} of SA, the lowest dose had the best effect on maize during drought. Moreover, it was shown that SA pre-treatment delayed maize leaf rolling, which is a visual sign of water loss through drought stress to the plant. Hence, it can be concluded that SA reduces water loss and increases the activity of antioxidant enzymes [103].

Another species on which tests have been conducted are lemongrass (*Cymbopogon flexuosus* Steud. Wats.) varieties (Neema and Krishna). Under drought stress conditions, plants with foliar application of SA obtained higher chlorophyll and carotenoid levels. The growth parameters of lemongrass also increased [104]. Furthermore, research has also been conducted on zoysiagrass (*Zoysia japonica*). After exogenous SA pretreatment, they showed an increase in photosynthetic pigments, net photosynthesis rate, and enhancements in the antioxidant system. Thus, salicylic acid was found to reduce the effect of drought on zoysiagrass. Among the tested concentrations of 0.0001, 0.0005, and 0.001 mol·L^{-1} salicylic acid, 0.0005 mol·L^{-1} SA had the most beneficial effect [105]. Similar results were obtained on lolium grass (*Lolium perenne* cv. "Numan"), where an increase in the content of chlorophyll a and b was recorded after the foliar application of SA. These results demonstrate the potential of SA in combating the effects of drought on grasses [106].

As with the other antitranspirants in this group, examples of studies are shown in Table 2. Studies relating to this AT are on a broad spectrum, covering the physiological, biochemical, and yield parameters of plants in the *Poaceae* family. Measurements were carried out on plants such as barley, lemongrass, lolium grass, maize, pearl millet, rice, sorghum and wheat.

Table 2. Examples of studies on using metabolic antitranspirants (chitosan, fulvic acid, salicylic acid) concerning drought stress on *Poaceae* plants.

	Morphological Parameters			Physiological Parameters			Biochemical Parameters			Yield and Yield Components		
	Chitosan	**FA**	**SA**	**Chitosan**	**FA**	**SA**	**Chitosan**	**FA**	**SA**	**Chitosan**	**FA**	**SA**
Barley	[72,73]		[84]	[72,73]		[82,83,85]	[72,73]		[82–85]	[72,73]		
Bermudagrass				[107]			[107]					
Creeping bentgrass				[71]			[71]					
Lemongrass			[104]						[104]			[104]
Lolium grass									[106]			
Maize	[51,60,75,108,109]	[78,79]	[32,100,102,110,111]	[51,60,74,75,109]	[76,78–81]	[101–103,110,112]	[51,60,74]	[76,78–81]	[101–103,110]	[60,109]	[76,78,80,81]	[32,100,110,111]
Pearl millet	[70]		[113]	[70]		[113]	[70]		[113]	[70]		[113]
Rice	[67,69]		[86,114–118]	[67,119]		[86,114,115,118,120,121]	[67,119]		[86,114–118,121–123]	[67,119]		[116–118,121,123]
Sorghum	[124]		[98,99]	[124]		[97]	[124]		[98,99]	[124]		[98,99]
Wheat	[55,61,62,64,77]	[125]	[88–93,95,96,113,126–129]	[55,63,65,66]		[87,88,92,113,126–129]	[55,61,63,65,66,77]	[125]	[87,88,90,92–96,113,126,128–131]	[55,61–64,66]	[125]	[87–92,113,126,128,130,131]
Zoysiagrass						[105]			[105]			[105]

FA—fulvic acid, SA—salicylic acid.

5. Reflective Antitranspirants

5.1. Kaolin

Kaolin is popular antitranspirant and a naturally occurring aluminosilicate mineral that is often found on the agricultural formulation market under the commercial name Surround®. It is a powder that is mixed with water and then sprayed on crops, on which it forms a white coating to protect the plants [132]. Youssef et al. [133] conducted studies under different levels of drought stress (100, 80, and 60% ETc evapotranspiration) on Giza 10 maize. When 5% kaolin was applied at both 60 and 80% ETc, higher plant height, leaf flag fresh, and dry weight results were achieved compared to maize samples with 100% ETc and without kaolin. Similar effects were obtained for yield indices such as cob length, number of grains per cob, and 100-grain weight. These results show that using kaolin makes plants use up to 40% less water and can save irrigation water for maize. Moreover, with the application of this AT, the same or even higher yields can be obtained [133]. In studies conducted on rice and different rates of kaolin (4%, 6%, and 8%), an increase in dry matter was noted on treated plants under water deficit conditions. The best results were obtained with 6% kaolin, at which an increase in straw yield, grain yield, and biological yield was recorded, while a dose of 8% kaolin was not as effective [134]. The positive effect of this antitranspirant has also been confirmed by studies conducted on wheat (cv. Gimeza 7). The use of kaolin under drought conditions contributed to improved growth parameters, yield components, photosynthetic pigments, and carbohydrate constituents [135]. Another study on wheat (cv. Sakha 93) revealed that the application of kaolin at both 4% and 6% resulted in increases in the plant height, leaf area, and dry weight of plant roots compared untreated plants under water stress conditions. Moreover, it also positively affected yield components such as 1000-grain weight, number of grains per plant, and dry weight of grains per plant [125].

Table 3 presents a set of studies relating to the application of kaolin on *Poaceae* plants in the context of drought. It can be observed that research on its effect on physiological parameters is not popular. Therefore, the proportion of experiments covering this issue should be increased. Furthermore, it is noticeable that measurements were mainly conducted on the most popular cereals, such as barley, maize, rice, and wheat.

5.2. Magnesium Carbonate $MgCO_3$

Studies regarding the use of magnesium carbonate (6 and 10%) on wheat have shown the beneficial effect of this antitranspirant on plant height, chlorophyll a and b, leaf area, and 1000-grain weight under water stress conditions [125]. Other studies under drought conditions have confirmed that this AT allows less reduction in wheat yields. Measurements proved that drought reduced grain yields by 24.25%. However, after the application of this antitranspirant, the negative effect of drought was mitigated to 9.98% [136]. A reduction in yield losses during drought was also observed in barley [137]. The useful influence of $MgCO_3$ in offsetting the negative effects of drought in barley has also been confirmed by subsequent research. These studies showed that the substance increases water use efficiency [138]. Another study on the same plant showed that using $MgCO_3$ under drought conditions also positively affects chlorophyll and RWC, indicating that $MgCO_3$ has a high potential for use on crops in arid and semi-arid areas [82].

Through analyzing previous studies, it can be seen that a similar trend is apparent for $MgCO_3$ as for kaolin. Studies covering physiological parameters are scarce and therefore should be continued. A detailed overview covering the different groups of plant parameters studied in relation to drought and the application of this AT is summarized in Table 3.

Table 3. Examples of studies on the use of reflective antitranspirants (kaolin, magnesium carbonate) concerning drought stress on *Poaceae* plants.

	Morphological Parameters		Physiological Parameters		Biochemical Parameters		Yield and Yield Components	
	Kaolin	**$MgCO_3$**	**Kaolin**	**$MgCO_3$**	**Kaolin**	**$MgCO_3$**	**Kaolin**	**$MgCO_3$**
Barley		[137,138]		[82,138]		[82,137]		[137,138]
Maize	[32,133]				[133,139]	[139]	[32,133,139]	[139]
Rice	[140]	[141]				[141]	[134,140]	[141]
Wheat	[125,135]	[125,136]			[125,135]	[125]	[125,135]	[125,136]

6. Risks, Uncertainties, and Future Perspectives for the Use of Antitranspirants

Despite a large number of studies reporting beneficial effects of antitranspirants, some also indicate their absence or negative effects in terms of drought stress mitigation. For example, Ouerghi et al. [30], in their study on durum wheat and barley, did not observe a significant effect of using Vapor Gard on the photosynthetic rate. Thus, this AT did not reduce the negative effect of water stress on this parameter. In measurements using magnesium carbonate, this AT had no clear effect on wheat parameters such as the number of spikes per plant, the number of grains per spike, and the number of grains per plant [125]. Furthermore, the results of experiment on maize and winter wheat indicated an increase in drought sensitivity after treatment with salicylic acid [112]. Moreover, pre-treatment with SA reduced drought tolerance in the wheat cultivar Chinese Spring, but there was no effect on another cultivar tested called Cheyenne [129]. This demonstrates that SA can have different effects on various cereal varieties. Other studies on wheat have shown even more divergent results. Two wheat cultivars on which an exogenous SA was applied under normal conditions demonstrated increased fresh and dry mass of shoots and roots. However, under water stress and with the same SA dose, one cultivar showed a reduction in shoot fresh and dry weights, while the other presented an improvement [127].

The above results indicate that sometimes inconclusive effects regarding the use of antitranspirants have been obtained on *Poaceae* plants. At the same time, it should be noted that scientists are reluctant to publish inconclusive results, and it is also unclear how many parameters and results have been omitted in articles. Furthermore, it is also problematic that the results obtained regarding the use of antitranspirants may depend on the type of plant, the antitranspirant, its dose, the time of application, as well as the characteristics of the environment, and it is often difficult to compare previous studies with each other. This review shows that, despite years of research on various species, further studies are needed to identify factors that directly influence the achieved effects. Once more research has been carried out, thorough analyses need to be conducted to determine which antitranspirant and at what dose will be the most effective solution to offset the effects of drought stress for a given species.

Concerning plants belonging to the *Poaceae* family, particularly the key food-safety crop, it is extremely important to carry out financial analyses. Therefore, estimating exactly how much financial input will be needed to apply antitranspirants in the field is necessary. This is crucial from the farmer's point of view, as the use of AT will not make sense if the total cost of treatment is greater than the damage caused by the drought. Therefore, before the use of AT becomes widespread, there is a need for more research combined with crop-specific cost–benefit analyses.

Furthermore, it should be noted that many uncertainties are still associated with the widespread application of antitranspirants in agriculture. Mphande et al. [14] in their review article, highlight the risks of AT application in terms of potential negative environmental effects. The researchers suggest that, while the effects on AT on individual species are being studied, a broader approach concerning the environment is lacking. In addition, scientific reports shows that these products may also reduce the occurrence of plant pests and, even worse, their natural enemies. Mphande et al. [14] emphasize the need for research in this area to obtain a comprehensive picture of the impact of antitranspirants.

7. Conclusions

The present review demonstrates that further measurements are still needed despite the many studies in the field of antitranspirants. The summaries of AT applications for individual *Poaceae* plants and for parameter groups presented in this article have identified less common research areas relating to drought. It was concluded that it is desirable to increase the number of experiments involving the application of Vapor Gard to plants other than wheat. Looking at the AT analyzed, relatively few articles examine the impact of fulvic acid application in the context of drought. Concerning the reflective AT group, emphasis should be placed on the study of physiological parameters, as most of the articles published to date practically disregard this aspect. Furthermore, when analyzing the studies previously carried out, it is noticeable that scientists mainly focus their research on the more common cereals, such as wheat or maize, and less emphasis is placed on the other plants of the *Poaceae* family. On the positive side, the scientific community's interest in antitranspirants has been growing in recent years, and more and more work is focusing on identifying their effects on plants [58]. This gives hope that soon all of the gaps mentioned above will be filled, and as a result, there will be a significant increase in the knowledge of AT applications.

This review shows the great potential of using antitranspirants to reduce the impact of drought stress of plants in the *Poaceae* family. It demonstrates that antitranspirants can mitigate the adverse effects caused by this stress and improve many plant growth and yield parameters. However, it must be taken into account that the plant species, genotype, environment, type of antitranspirant, and rate of application are key factors that influence the final result and effectiveness. The differential response of plants to AT application depending on several factors has already been signalled in previous work [27,142]. Furthermore, it is important to note that, often in field crops, there is not only just one stress factor but several occurring simultaneously. It is also not uncommon to see a combination involving not only two abiotic factors (e.g., drought and high temperature) but also stresses categorized as abiotic and biotic occurring simultaneously. A prime example is the occurrence of drought together with pathogen infection [143,144]. Scientists emphasize that it is crucial for agricultural production to find ways to allow plants to comprehensively cope with simultaneous stresses of both biotic and abiotic origin [145]. Therefore, future research should continue to analyze the interaction and joint effects of a wide range of stresses on crops and look for solutions that can offset their negative effects on plants. It was also noted that it would be interesting to perform measurements on the joint effects of agronomic treatments and antitranspirant applications [27,142]. It should also be noted that this review and previous studies practically do not consider financial factors. Before the use of AT as a solution to offset the effects of drought stress becomes widespread, detailed analyses should be carried out regarding what costs the farmer will have to bear for applying this treatment. This review shows that antitranspirants have great potential for drought mitigation in *Poaceae*, but further research is still required to obtain a full view of the impact of their widespread use.

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