

# The potential of antitranspirants in drought management of arable crops: a review

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**Harper Adams  
University**

1 **The potential of antitranspirants in drought management of arable crops: a**  
2 **review.**

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9 **Abstract**

10 About 80% of global farmland is under rain-fed conditions and most of it prone to  
11 drought, which limits crop productivity. Due to climate change, drought will  
12 become more frequent and severe threatening world food security.  
13 Antitranspirants, materials that reduce transpiration, could potentially result in  
14 greater food production by realising more of a crop's potential yield during  
15 drought. Despite antitranspirants also reducing photosynthesis, research has  
16 shown that they can mitigate drought stress resulting in increased grain yield.  
17 Although this paper is not restricted to specific years, part of it is a systematic  
18 review of 173 original research articles published between 2009 and 2018. Overall,  
19 the analysis suggests that interest in the potential of antitranspirants is growing.  
20 One major achievement in antitranspirant research during the past decade was  
21 establishing the optimal timing of application of the substances, which is linked to  
22 reproductive processes most vulnerable to drought. Despite research evidence of  
23 the efficacy of antitranspirants in ameliorating drought stress, they are not widely  
24 used for commercial arable crop production. However, in fruit horticulture,

25 products with antitranspirant effects are being used for various non-antitranspirant  
26 purposes such as synchronising fruit ripening, enhancement of nutritional quality,  
27 protection against sunburn and controlling diseases and insect pests.

28 -----

29 Keywords: Stomatal conductance, terminal drought, drought amelioration

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51 **1.0 Introduction**

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53 Future crop productivity and world food security will be undermined by severe and  
54 more frequent droughts and other abiotic stresses (IPCC, 2018), and reducing  
55 transpiration with antitranspirants (ATs) may have a role in ameliorating drought.  
56 About 80% of the total cropped area globally is under rain-fed agriculture (Huang  
57 et al., 2019, supplementary information), and prone to droughts  
58 (<https://youtu.be/Sy0u8LCZK50>, Singh et al., 2017). Under a frequent drought  
59 scenario predicted for the future, reducing transpirational water loss will be  
60 required to obtain improvements in grain yield. The rapidly increasing world  
61 population, projected to reach 9.8 billion by 2050 (United Nations, 2017), will put  
62 pressure on food demand. Cereal production must increase by 26% from 2.8 to  
63 3.5 billion tonnes, as from the 2014 baseline (Hunter et al., 2017, supplementary  
64 data) in order to avert global food insecurity.

65 One neglected agronomic technique that has potential to significantly contribute to  
66 drought stress amelioration in food crop production is the use of ATs. ATs are  
67 substances that are applied on leaves to reduce transpiration and hence improve  
68 plant water potential (del Amor et al., 2010). However, to avoid reducing grain  
69 yield biomass due to depression of transpiration, drought is a precondition as past  
70 researched demonstrated (e.g. De and Giri, 1978 and del Amor et al., 2010). In  
71 addition, a comprehensive study by Kettlewell et al. (2010) showed that AT should  
72 target the most drought sensitive stage to avoid counterproductive effects. The  
73 potential of ATs to ‘waterproof’ the most critical crop development stages  
74 (Kettlewell, 2014) through reduced transpiration and improve water use efficiency  
75 (WUE) during drought is an active area of research.

76 Detailed reviews of drought avoidance and other plant adaptive strategies to water  
77 deficit stress have been dealt with in previous reviews (e.g. Farooq et al., 2009  
78 and Luo, 2010). Also, not discussed here are silicon, and biostimulants like proline  
79 and the various compounds extracted from seaweed (such as betaines). These  
80 products have drought ameliorative effects which are unrelated to transpiration  
81 such as up-regulating flavonoid biosynthesis and antioxidant activities (Ma et al.,  
82 2015) and reducing osmotic stress (Ghaffari et al., 2019; Khan et al., 2009).

83 Thirty-eight years have passed since the last general review on ATs by Solarova  
84 et al., (1981). This may in part be due to the negative research conclusion in the  
85 late-1970s, which was echoed by Solarova et al., (1981) that ATs were not  
86 generally recommended for use in arable crop production. Much of the research  
87 on ATs in the past was conducted between 1950 and 1979 (Kettlewell et al.,  
88 2010). Researchers at that time found that although ATs improved the water  
89 status of plants by reducing the rate of transpiration, the products also reduced the  
90 intake of carbon-dioxide (CO<sub>2</sub>) and hence the rate of photosynthesis (Kettlewell et  
91 al., 2010). In fact, ATs were found to be less permeable to CO<sub>2</sub> than water vapor  
92 (Plaut et al., 2004; Woolley, 1967). Because of this, the conclusion made was that  
93 ATs were unsuitable for use in crop production except where survival of the plant  
94 was at stake, in which case photosynthesis was of secondary importance (Das  
95 and Raghavendra, 1979; Davenport et al., 1972). This explains the decline in AT  
96 research after the 1970s and why the technique remains largely neglected.  
97 However, it is important to note that photosynthesis is partially reduced and not  
98 completely stopped by ATs, and that the reduction in carbon assimilation is  
99 outweighed by the benefit if the products are applied to protect the most drought  
100 sensitive stage (Kettlewell, 2014). Das and Raghavendra (1979) concluded that

101 AT products were only economically feasible for specific enterprises such as high  
102 value fruit production. Although AT products currently have commercial relevance  
103 in fruit horticulture (e.g. for protection against sunburn, synchronising ripening and  
104 pest protection), there is no evidence that they are being used for drought  
105 amelioration. This suggests that they may still be not be cost-effective for low  
106 value crop production systems like arable farming.

## 107 **2.0 Antitranspirant classes**

108 The mode of action of each one of the three classes of ATs and their  
109 representative compounds (Table 1) are reviewed below.

### 110 **Position for Table 1**

111

## 112 **3.0 Research topics between 2009 and 2018**

113

114 A decadal overview of AT classes used and research objectives was done using  
115 original research articles published between 2009 and 2018. Our sampling of  
116 research papers in this decade was for a more quantitative assessment aiming to  
117 reveal the trends in research in recent years. Non-drought amelioration uses of  
118 ATs were included in the analysis for the purpose of demonstrating the wider  
119 range of uses of AT products. Papers were accessed using the search engines  
120 *Google Scholar* and the Harper-Adams University's electronic library system, with  
121 links to several databases including *BioOne*, *Web of Science* and *ScienceDirect*  
122 which were relevant to this study. A total of 173 peer-reviewed original research  
123 papers were collated and analysed on the basis of crop type, AT type and

124 research objective (Table 2). The trend of publications shows that research  
125 interest in the potential of ATs is increasing.

## 126 **Position for Table 2**

127

### 128 *3.1 Reflective antitranspirants*

129

130 As their name suggests, reflective ATs function on the basis of reflectance to  
131 minimise leaf temperature and consequently the transpiration rate (Glenn, 2012).

132 Once reflective ATs have been applied, the foliar characteristics to absorb, reflect  
133 and transmit light are altered, modifying leaf temperature and gas exchange

134 variables (Abou-Khaled et al., 1970). Kaolin (an aluminosilicate,  $\text{Al}_4\text{Si}_4\text{O}_{10}(\text{OH})_8$ ,

135 Cantore et al., 2009) is foremost among the reflective ATs being the most studied

136 as the survey of published literature revealed (e.g. between 2009 and 2018, there

137 were 78 original research papers on kaolin versus 18 on the other reflective ATs).

138 Ordinary kaolin, in its crude form, has impurities of titanium dioxide ( $\text{TiO}_2$ ) and

139 ferric oxide ( $\text{Fe}_2\text{O}_3$ ), but as a particle film technology product, it is upgraded to a

140 highly light reflective, fine grained ( $< 2 \mu\text{m}$ ), low-abrasive product of over 99%

141 purity, after a spreader-sticker is added (Brito et al., 2019; Glenn and Puterka,

142 2005). Applied to the leaf surface, it forms a whitish film (Boari et al., 2015) by

143 which the optical properties of the target leaf are transformed.

144 With enhanced reflective properties, particle film kaolin is more effective than

145 unprocessed kaolin in minimising the heat load on leaf surfaces, as more infrared

146 radiation and ultraviolet rays are reflected (Brito et al., 2019; Glenn and Puterka,

147 2005). Despite reduced transpirational cooling, previous studies reported leaf

148 temperature reduction (or canopy temperature depression) effect due to kaolin of  
149  $>3^{\circ}\text{C}$  e.g. by  $5.6^{\circ}\text{C}$  in walnut (Gharaghani et al., 2018), and between 3 and  $4^{\circ}\text{C}$  in  
150 Valencia orange - corresponding to a 22-28% decline in transpiration -  
151 (Abou-Khaled et al., 1970), similar to  $3.8^{\circ}\text{C}$  in snap beans (AbdAllah et al., 2019).  
152 Kaolin was effective in reducing transpiration and leaf temperature (by  $1.4^{\circ}\text{C}$ ) in  
153 field beans (Tworkoski et al., 2002). However, kaolin can have an opposite effect  
154 on leaf temperature if the target plant is not under drought stress. In grapes plants  
155 sprayed with kaolin, Brillante et al., (2016) observed an increase in leaf  
156 temperature of  $1.47^{\circ}\text{C}$  in well-watered versus a  $1.30^{\circ}\text{C}$  decrease in water-stressed.  
157 The increase in leaf temperature under well-watered conditions is attributable to  
158 kaolin occluding stomata, reducing the transpirational cooling effect in the  
159 process. This means that to reduce the negative effects of high temperature on  
160 crop physiology, drought stress is a requisite. This may not be true in all cases as  
161 kaolin is widely used to solely protect fruit from sunburn. In mung beans (*Vigna*  
162 *radiata* L), water deficit stress was demonstrated as a prerequisite to kaolin  
163 application for improved yield (De and Giri, 1978). Kaolin can also cause an  
164 increase in leaf temperature under low photosynthetic photon flux density  
165 (Brillante et al., 2016) and also lead to reduced photosynthesis (Brito et al., 2019).  
166 In apples, (Gindaba and Wand, 2005) observed up to  $1.1^{\circ}\text{C}$  increase in leaf  
167 temperature. Further, by partially occluding stomata, reflective ATs can also  
168 partially contribute to a reduced gas exchange profile of the pores (Boari et al.,  
169 2015).

170 For transpiration to occur, a vapour pressure gradient between the leaf and the  
171 surrounding air is necessary (Bloomfield et al., 2019; Medina and Gilbert, 2015).  
172 By lowering the leaf heat energy balance, the vapour pressure gradient between



173 the leaf and the air is narrowed, thereby decreasing the transpiration rate (Kostka  
174 and Aquatrols Corporation of America, 2018). Additionally, particle films confer  
175 protection to the photosynthetic apparatus, particularly photosystem II reaction  
176 centres against excessive irradiance (P.S.O. da Silva et al., 2019; Dinis et al.,  
177 2018). This suggests that plants that have been sprayed with particle films can  
178 have not only higher but also longer-lasting photosynthesis before initiation of  
179 senescence. While reflecting infrared radiation and ultraviolet rays, reflective ATs  
180 also reduce the amount of photosynthetically active radiation (PAR) absorbed  
181 (Brillante et al., 2016) and hence have a negative effect on photosynthesis.  
182 However, depending on the canopy architecture, reflection can result in a positive  
183 redistribution of light with an overall enhancement of whole canopy  
184 photosynthesis, especially in dense canopies (Brito et al., 2019; Glenn, 2012).

185 The two calcium-based reflective ATs,  $\text{CaCO}_3$  and  $\text{CaO}$  have a similar mode of  
186 action to kaolin. At the time of this review, there was no known study on arable  
187 crops involving these ATs, and only a few on non-arable species (e.g. banana (El-  
188 Khawaga, 2013) and grapes (P.S.O. da Silva et al., 2019). This may be explained  
189 by the novelty of calcium in particle films (Paulo Silas Oliveira da Silva et al.,  
190 2019). In grapes and coffee,  $\text{CaO}$  was found to have longer lasting physiological  
191 effects than  $\text{CaCO}_3$ . In 28 days after application (DAA) the luminosity value of  
192  $\text{CaCO}_3$  declined by 31% against 17% for  $\text{CaO}$ . Besides higher luminosity,  $\text{CaO}$   
193 maintained reduced leaf temperature and gas exchange variables and higher  
194 chlorophyll (P.S.O. da Silva et al., 2019; Paulo Silas Oliveira da Silva et al., 2019).  
195 To obtain a complete and equivalent foliar coverage to that of  $\text{CaCO}_3$ , the  
196 concentration of  $\text{CaO}$  needs to be doubled (e.g. 20% w/v  $\text{CaO}$  versus 10% w/v  
197  $\text{CaCO}_3$ ). The higher concentration of  $\text{CaO}$  may account for this difference in

198 duration of efficacy (Paulo Silas Oliveira da Silva et al., 2019). Besides calcium  
199 compounds, reflective ATs less researched include any other mineral-based  
200 products such as magnesium carbonate ( $MgCO_3$ , Al-Desouki et al., 2009) and  
201 magnesium silicate ( $MgO_3Si$ , Schrader, 2011). One environmental concern with  
202 reflective ATs that needs addressing is the effect on non-target organisms as  
203 further reviewed in the last section.

### 204 3.2 *Metabolic or stomata-closing antitranspirants.*

205

206 Metabolic ATs are a group of substances that have hormone or hormone-like  
207 effects, inducing partial stomatal closure by acting on guard cells (AbdAllah et al.,  
208 2018). Prominent in this class is exogenous abscisic acid (ABA) in its naturally-  
209 occurring bioactive form (*S*)-*cis*-ABA (*s*-ABA) or a commercially available mixture  
210 with the synthetic (*R*)-*cis*-ABA (J. Li et al., 2017). ABA signalling causes an efflux  
211 of ions from guard cells, and water by osmosis, leading to flaccidity of the cells  
212 with concomitant stomatal closure (Kim et al., 2012; Munemasa et al., 2015).  
213 Several studies have reported drought tolerance and yield improvement effects of  
214 exogenous ABA e.g. in artichoke (Shinohara and Leskovar, 2014) and wheat  
215 (Travaglia et al., 2010; Zhang et al., 2016).

216 ABA as an AT is perhaps the most prominent product in this group, as chitosan  
217 and fulvic acid are not solely ATs but are also used as biostimulants to improve  
218 uptake of both major and trace elements - even on crops under well-watered  
219 conditions - (Pettit, 2004; Sootahar et al., 2019). Plant biostimulants are  
220 substances or micro-organisms that are applied on plants on or in their growth  
221 medium to enhance growth by boosting nutrient uptake or tolerance to biotic or  
222 abiotic stress (Brown and Saa, 2015). The mechanism of interaction between

223 exogenous ABA as an AT and endogenous ABA is not well understood. However,  
224 it is known that benefits from endogenous ABA are short-term and occur only  
225 under mild drought stress (Sreenivasulu et al., 2012). This corroborates with the  
226 short-lived (less than seven days) effects of exogenous ABA on stomatal closure  
227 in wheat (Travaglia et al., 2010). During reproductive-stage drought stress,  
228 endogenous ABA may induce premature senescence with undesirable effects  
229 such as reproductive organ abortion (Pang et al., 2017); and loss of grain number  
230 if drought coincides with meiosis in grain-bearing crops like cereals and pulses  
231 (Dolferus et al., 2011; Ji et al., 2011). Applying ABA as an AT during meiosis may  
232 therefore negatively affect crop productivity. In commercial fruit horticulture, ABA  
233 is used for fruit quality enhancement, particularly of table and wines grapes  
234 (Gonzalez et al., 2018).

235 Closely connected to ABA signalling is the metabolic pathway regulated by  
236 chitosan. In field bean plants (*Phaseolus vulgaris* L.), Iriti et al. (2009) found that a  
237 foliar chitosan application led to stomatal closure and a reduction in transpiration.  
238 An increase in the endogenous ABA concentration (more than threefold) and that  
239 of hydrogen peroxide ( $H_2O_2$ ) was also observed one day after spraying. The  
240 intrinsic WUE was not significantly improved. Chitosan is known to cause stomatal  
241 closure by promoting biosynthesis of ABA, but the mechanism by which this is  
242 accomplished is not well understood (Hidangmayum et al., 2019). Although Iriti et  
243 al. (2009) did not explain the link between ABA and  $H_2O_2$ , in faba beans (*Vicia*  
244 *faba* L.), it is known that ABA signalling downstream induces the production of  
245  $H_2O_2$ , as a secondary messenger, to cause stomatal closure (Arve et al., 2014).  
246 Calcium ions, nitric oxide and reactive oxygen species are among the other  
247 secondary messengers in the ABA signalling network (Lee and Luan, 2012).

248 The other biostimulant-antitranspirant in the metabolic AT class is fulvic acid.  
249 Fulvic acid is a by-product of organic matter decomposition that dissolves in both  
250 alkaline and acid solutions (Klucakova et al., 2000). It is a variable mixture of both  
251 aliphatic and aromatic organic acids, which are similar to humic acids but more  
252 reactive (Pettit, 2004). Along with this diverse chemical constitution, fulvic acid has  
253 both AT and biostimulant functions. As an AT, the effects of fulvic acid on gas  
254 exchange physiology have been studied in a number of crops and genotypes. In  
255 maize growing under drought stress (soil moisture at 35% of field capacity), Anjum  
256 et al. (2011) found that fulvic acid applied at the tasselling stage insignificantly  
257 increased stomatal conductance by 13% while transpiration rate, net  
258 photosynthesis and WUE were significantly improved, implying that fulvic acid  
259 acted as a biostimulant instead. Zhang et al. (2016) found that while exogenous  
260 ABA significantly reduced both stomatal conductance and transpiration rate in  
261 wheat under mild drought stress, fulvic acid was not effective. Zhang et al. (2016)  
262 and Anjum et al. (2011) apparently contradict Xudan (1986), who observed that  
263 fulvic acid was effective in reducing stomatal conductance in wheat and improving  
264 water potential and grain yield. This discrepancy might be attributed not solely to  
265 genotypic and interspecific factors but also to the chemical variability of fulvic acid.  
266 Working on wheat, Dunstone et al. (1988) confirmed that although fulvic acid  
267 reduced stomatal conductance, its effects were highly variable. In a glasshouse  
268 experiment, a reduction in stomatal conductance was recorded only in well-  
269 watered but not in drought stressed plants. Furthermore, while in the four most  
270 responsive genotypes the reduction ranged between 15 and 40%, it was only  
271 between 1 and 3% in the least. In addition, for the highly responsive genotypes,  
272 the effect was stable in growth cabinets where artificial light was used, but rapidly

273 decayed under natural light, becoming marginally significant to non-significant  
274 within four to seven days. The heterogenous composition of the molecular  
275 structure of fulvic acids and other biostimulants, particularly the functional groups,  
276 affects their chemical and physico-chemical properties (Bai et al., 2015;  
277 Klucakova, 2018) and thus may partly explain the contradictory findings. For, this  
278 reason, replicating experiments involving these products is impossible as there is  
279 not a single mode of action (Brown and Saa, 2015). A consideration of these  
280 findings by different researchers suggests that the mechanism of drought  
281 amelioration by fulvic acid may not significantly be mediated by stomatal  
282 movement but rather through its biostimulant functionalities. Fulvic acid  
283 biostimulant functionalities are its roles or functions for which it has been found  
284 to be more effective or better suited as a biostimulant (e.g. enhancing bioactivity of  
285 glutamic oxaloacetic transaminase to improve nutrient uptake in wheat, Zhimang  
286 et al., 2001 and increasing gas exchange and carbon assimilation, Anjum et al.,  
287 2011, which are opposite effects of an AT).

288 Besides modifying gas exchange variables, both chitosan and fulvic acid confer  
289 drought tolerance through biostimulant functions. By inducing antioxidant  
290 activities, they enhance scavenging for reactive oxygen species and promote  
291 cellular membrane integrity (Bistgani et al., 2017; Z. Li et al., 2017). In addition to  
292 improving the water potential of droughted wheat plants, fulvic acid was found to  
293 alleviate the loss of chlorophyll and enhance the uptake of phosphorus by roots  
294 (Xudan, 1986). Z. Li et al. (2017) found that chitosan not only improved water  
295 balance in droughted white clover but also up-regulated antioxidant activity and  
296 chlorophyll content.

297 The short-lived effects of metabolic ATs and that the use of chitosan and fulvic  
298 acid is not restricted to drought stress conditions imply that concerns that these  
299 ATs may hinder crop growth and productivity in an event of improved soil moisture  
300 status (e.g. following rainfall) are unnecessary.

301 Phenyl mercuric acetate (PMA), a popular subject of metabolic AT research in the  
302 past (Sinclair et al., 1975), was found to be toxic (Das and Raghavendra, 1979). It  
303 disappeared from AT research but was still used as a fungicide before being  
304 banned in some countries (Nandi, 1985). India is apparently the only country  
305 where the use of PMA as an AT (e.g. Pandey et al., 2017 and Kumar et al., 2018)  
306 remains legal.

307 Another compound with an ABA-related mechanism is pyrabactin, a synthetic  
308 growth inhibitor with a sulphonamide functional group (Cao et al., 2013). Though  
309 not among the popularly known ATs, it has a mode of action similar to ABA and is  
310 its agonist but not its structural analogue (Fan et al., 2015). In peas (*Pisum*  
311 *sativum* L.), Puli and Raghavendra (2012) found that pyrabactin had similar effects  
312 to ABA on stomatal closure. Stomatal apertures decreased by a larger percentage  
313 in plants where pyrabactin and ABA were used together, suggesting a synergistic  
314 mechanism. Nevertheless, pyrabactin may not play a significant role in drought  
315 stress mitigation as its bioactivity in vegetative parts is weaker than in seeds,  
316 where it inhibits germination (Cao et al., 2013; Park et al., 2009). There is limited  
317 published information on pyrabactin as an AT. None of the studies cited here (and  
318 more e.g. Park et al., 2009, Yu et al., 2017 and Han et al., 2019) were conducted  
319 in the field or on well established crops to provide conclusive evidence of the  
320 potential of pyrabactin as an AT.

### 3.3 *Film-forming antitranspirants*

322

323 The currently available film-forming ATs are mostly water-emulsifiable organic  
324 polymers that form films after a spray application has dried (Moftah and Al-  
325 humaid, 2005). The films act as a physical barrier over stomata by which  
326 transpirational water loss is reduced.

327 Di-1-*p*-menthene (pinolene) is the oldest film-forming AT with one of the earliest  
328 references being Williamson (1963). Under glasshouse conditions, (Faralli et al.,  
329 2016) compared the drought ameliorative effects of di-1-*p*-menthene and poly-1-*p*-  
330 menthene on oil seed rape. Both compounds significantly reduced gas exchange,  
331 however, di-1-*p*-menthene was not only more effective in suppressing stomatal  
332 conductance (by 50% against 11%) but also sustained the effect for a longer  
333 period (>14 days versus < nine days). The yield component results were  
334 consistent with the stomatal conductance readings, with di-1-*p*-menthene having  
335 higher values for number of pods per plant and seed biomass, suggesting that the  
336 negative effect on CO<sub>2</sub> fixation was compensated for by increased WUE. The  
337 efficacy of di-1-*p*-menthene in suppressing gas exchange has also been  
338 demonstrated on horticultural species, especially grapes, and not only for foliar but  
339 also bunch transpiration (Fahey and Rogiers, 2018; Vaio et al., 2019). In an AT  
340 comparative study on droughted grapes, di-1-*p*-menthene was found to depress  
341 photosynthesis and intrinsic WUE while kaolin enhanced these variables (Brillante  
342 et al., 2016). This suggests that different classes of AT do not induce similar  
343 physiological responses.

344 One group of compounds in this class, paraffinic hydrocarbon waxes - Folicote -  
345 (Francini et al., 2011; Fuehring, 1973) was effective in suppressing gas exchange

346 variables and increasing yield (e.g. between 11 and 17% in maize (Fuehring and  
347 Finkner, 1983) and five to 17% in sorghum (Fuehring, 1973). However, paraffinic  
348 hydrocarbon waxes do not feature in recent AT research. Other less important  
349 compounds, on which limited research has been published include vegetable oils  
350 and acrylic polymers. The former may become important in future as they are not  
351 only cheaper (Granger and Trager, 2002) but more readily available than synthetic  
352 products.

353 A film-forming AT end-user advantage over other AT classes is the less frequent  
354 application, typically once for 30 days for an acrylic polymer in a glasshouse (Plaut  
355 et al., 2004), though for poly-1-*p*-menthene it was less than nine days in the OSR  
356 study above. In comparison, weathering agents can significantly reduce the foliar  
357 coverage and efficacy of reflective ATs to less than half a month (e.g.  $\text{CaCO}_3$   
358 (P.S.O. da Silva et al., 2019). As for metabolic ATs, their effects generally last for  
359 a few days (Travaglia et al., 2010), being controlled by the plant biochemistry  
360 since they are absorbed unlike the other ATs.

361 Although the use of ATs is valid only under drought stress conditions, in an event  
362 of improved soil moisture status due to rainfall, it would be desirable to remove  
363 them from the plant surface, particularly film antitranspirants. The importance of  
364 removing film antitranspirants in an event of unexpected rains is one research gap  
365 that needs pursuing. However, in the case of cereal stands the impact of film  
366 antitranspirants will reduce over time as new leaves emerge and take their place  
367 at the top of the canopy. This is particularly relevant in this case as it is these later  
368 emerging leaves that act as the source of carbohydrates supplied to the growing  
369 grain.



370 Finally, one other concern during early AT research that is more relevant to film-  
371 forming types was the effect on leaf temperature. However, the review by Gale  
372 and Hagan (1966) shows that an intersection of high solar radiation and very low  
373 wind speed was required to significantly increase leaf temperature due to reduced  
374 transpiration. In fact, a 30% reduction of transpiration attributed to ATs was found  
375 to have no significant effect on leaf temperature (Gale and Poljakoff-Mayber,  
376 1965). However due to global warming, the use of reflective ATs may play a more  
377 important role in drought stress mitigation.

378

#### 379 *3.4 Carbon-dioxide: the climate change antitranspirant*

380 Anthropogenic activities have elevated levels of atmospheric CO<sub>2</sub> leading to  
381 climate change (IPCC, 2018). Elevated CO<sub>2</sub> reduces transpiration rate (e.g. up to  
382 30% in carnation plants), however there is no consensus due to environmental  
383 and interspecific differences (Xu et al., 2016). Drought, one of the consequences  
384 of climate change, reduces plant nutrient uptake (Nawaz et al., 2012). There is  
385 currently limited information on the interaction of antitranspirants, elevated CO<sub>2</sub>  
386 and drought. One particular source is del Amor et al. (2010) who tested the effects  
387 on pepper. They showed that under elevated CO<sub>2</sub> (2000 ppm) and drought,  
388 stomatal conductance was higher with antitranspirant (di-1-*p*-menthene)  
389 application four and eight days after spraying (when measurements were taken),  
390 although the difference was not significant. The corresponding CO<sub>2</sub> assimilation  
391 effect was inconsistent being significantly higher in antitranspirant treated plants  
392 four days after spraying, and becoming non-significant at eight days after  
393 spraying. The response of transpiration rate was consistent with stomatal  
394 conductance. Interestingly, benefits of elevated CO<sub>2</sub> were only attainable under

395 well irrigated conditions, with no significant difference between antitranspirant  
396 treated and untreated plants. These findings suggest that elevated CO<sub>2</sub> may not  
397 be as potent as di-1-*p*-menthene in suppressing gas exchange. Further, this may  
398 eliminate concerns of reduced transpiration-driven nutrient uptake by mass flow  
399 induced by elevated CO<sub>2</sub> and other factors that suppress transpiration (Mcgrath  
400 and Lobell, 2013). However, further research is needed to make well established  
401 conclusions on interactions between drought, ATs and elevated CO<sub>2</sub> and how  
402 these affect plant nutrition and growth of various crops. Other impacts of global  
403 climate change will reduce the availability of soil moisture in some cases and  
404 affect transpirational processes. This may make dynamic drought management  
405 become more important.

#### 406 **4.0 The basis for timing of antitranspirant application**

407

408 Drought has varying effects on crop performance depending on its timing in  
409 relation to crop growth stage (GS). In cereals, drought at any time before the end  
410 of grain filling will affect grain yield. However, the worst is terminal drought (soil  
411 moisture deficit during a crop's reproductive development stages) as it has a grain  
412 yield limiting effect by reducing grain number (Saradadevi et al., 2017).  
413 Reproductive processes such as meiosis and microgametogenesis that occur  
414 during booting are the most susceptible to abiotic stresses such as drought  
415 (Barber et al., 2015). There is a strong correlation between grain number per ear  
416 and grain yield (Liu et al., 2015). In rice Kato et al. (2008), found that a mild  
417 drought stress at meiosis triggered secondary rachis and spikelet abortion per  
418 panicle of 70% and 45% respectively while drought at panicle initiation did not  
419 cause abortion of these reproductive structures. In oil seed rape (*Brassica napus*)

420 Faralli et al. (2016) showed that improving the water status of drought-stressed  
421 plants with film-forming AT during the reproductive stage was positively correlated  
422 with not only an increase in the number of pods per plant but also the seed yield.  
423 The processes of microsporogenesis (involving meiosis in pollen mother cells) and  
424 microgametogenesis (development of microspores into mature pollen grains) are  
425 known to be more sensitive to water stress than their female counterparts (De  
426 Storme and Geelen, 2014; Jager et al., 2008). Sensitivity to drought is most critical  
427 at the young microspore stage during microgametogenesis (Dolferus et al., 2011;  
428 Ji et al., 2010). However, Barber et al. (2015) argued that due to the influence of  
429 environmental and genotypic aspects, it was not possible to associate the most  
430 sensitive development processes with any one particular GS. Nevertheless, it is  
431 considered to be during booting; and in wheat there is evidence that it occurs  
432 between GS41 and GS43 (Alghabari et al., 2013; Barber et al., 2015). While it is  
433 not until near anthesis that the male gametophyte begins to accumulate starch  
434 grains, the process begins earlier in the female gametophyte (Ji et al., 2010;  
435 Raghavan, 1988), implying that in early development, pollen grains accumulate  
436 less carbohydrate reserves than ovaries. This could partly explain the higher  
437 vulnerability of pollen grains to abiotic stress during this period compared to  
438 ovaries. It may be for the same reason that most of the abiotic stress research on  
439 reproductive performance has focussed on the male gametophyte. A study by  
440 Onyemaobi et al. (2017) involving reciprocal crosses between well-watered and  
441 water stressed wheat plants provides evidence. Onyemaobi et al. (2017) found  
442 that only four out of 13 genotypes showed the female gametophyte to be  
443 significantly more sensitive to drought than the male gametophyte. Nearly 70% of  
444 cultivars studied showed the male gametophyte to be more susceptible to water

445 deficit stress than the female counterpart. It is the susceptibility of these  
446 reproductive processes coinciding with terminal drought that forms the foundation  
447 for the timing of AT application.

## 448 **5.0 Re-evaluating antitranspirants**

449

450 With reproductive processes identified as the most sensitive to drought, AT  
451 application timed to protect these stages is expected to result in the highest  
452 possible benefits to grain yield under water stress. One of the important  
453 developments in AT research in the recent past has been the identification of the  
454 most critical stage at which to apply ATs in order to optimise their usefulness  
455 under drought conditions. Overall, early AT researchers overlooked the role of  
456 plant GS in modulating the efficacy of ATs leading to the erroneous conclusion in  
457 the 1970s that AT use was only recommended if plant survival was at stake due to  
458 the negative effects on photosynthesis. In fact, even in the 1970's, the necessity of  
459 studying the effects of timing of AT application was mentioned by Davenport et al.  
460 (1972).

461 There are two notable exceptions to early AT researchers overlooking the  
462 importance of development stage. Fuehring (1973) researched the effects of rate  
463 of application of three ATs (metabolic - atrazine and PMA and film-forming-  
464 Folicote) and of irrigation frequency on the transpiration and yield performance of  
465 sorghum. In addition, he tested the effects of timing of application of PMA sprayed  
466 on three sets of plants at eight days before booting, 20 days after booting and a  
467 third set receiving double sprays - once on each of these days- and the unsprayed  
468 control plants. He found that the effects on grain yield of the lower rates of

469 atrazine and PMA, and the higher rate of Folicote were not significantly different  
470 from the unsprayed control plants. However, the higher rates of atrazine and PMA  
471 and lower rate of Folicote increased yield. Concerning timing of PMA application,  
472 spraying at eight days before booting resulted in significantly the highest yield  
473 response followed by double sprays. This research showed that not only the type  
474 of compound but also the rate of AT application modulates agronomic efficacy.

475 Later, Patil and De (1978) conducted a similar study but on oilseed rape and using  
476 Mobileaf (film-forming AT), kaolin (reflective AT) and PMA (metabolic AT). All ATs  
477 improved grain yield above the unsprayed and droughted plants. PMA  
478 applications were repeated, at the initiation of flowering and during pod  
479 development. Since the treatments at these different GSs involved the same  
480 plants, there was no basis for a comparative analysis. Nevertheless, it is  
481 noteworthy to state that they focused on the most drought-sensitive stages.

482 Recent research has been more robust in terms of understanding timing effects of  
483 AT application. Results have shown that despite reducing photosynthesis, ATs  
484 applied within specific plant GS can improve the performance of crops growing  
485 under water stress. Kettlewell et al. (2010) found that di-1-*p*-menthene (film-  
486 forming AT) improved grain yield of droughted wheat if the reproductive stages  
487 most sensitive to drought stress were protected. They tested the timing response  
488 of winter wheat to di-1-*p*-menthene application at five GSs (GS described by  
489 Zadoks et al. (1974) as GS37, GS39, GS45, GS55 and GS69). Their results  
490 revealed that di-1-*p*-menthene was most beneficial to yield improvement if applied  
491 at GS37 and GS39, unlike at GS45. On the other hand, much later applications at  
492 GS55 and GS69 were counterproductive in that they reduced crop yield – thus  
493 being corroborative of the 1970s research conclusion. Further, the AT was also

494 found to reduce yield if soil water deficit was not high. Soil moisture deficit was  
495 earlier found as a precondition for kaolin application to obtain yield improvement in  
496 mung beans De and Giri (1978). These findings agree with the analysis presented  
497 by Gale and Hagan (1966). The importance of the shoot/root ratio theory as  
498 presented by Gale and Hagan (1966) suggests that antitranspirants would be  
499 more effective for plants with high values (i.e. higher shoot-to-root biomass, due to  
500 lower actual-to-potential evapotranspiration ratio under well-watered conditions,  
501 below 0.9). Their argument implies that antitranspirants should not be used where  
502 the shoot/root ratio is lower as evapotranspiration is higher, except in an event of  
503 abiotic stress such as reduced mineral uptake from the soil (e.g. due to drought)  
504 that leads to the breakdown of the photosynthetic machinery (chlorosis). In such a  
505 situation antitranspirants would have a reduced inhibitory effect on photosynthesis  
506 as the mesophyll resistance to CO<sub>2</sub> conductance is high. This analysis indicates  
507 that shallow-rooted plants, being more prone to drought stress, would need AT  
508 application before deep-rooted ones. Taken together, the works by De and Giri  
509 (1978) and Kettlewell et al. (2010) demonstrated that not only drought stress was  
510 required as a precondition for AT application but the crop growth stage most  
511 sensitive to water stress must be protected for ATs to improve crop yield.

512 As discussed by Barber et al. (2015), the period of pollen development can last  
513 several days within a spike and much longer in a crop due to asynchrony between  
514 the male and female gametophytes. For this reason, reproductive stages sensitive  
515 to drought damage have a wider span in a crop and are not limited to a single GS.  
516 Refining limits within which farmers may apply AT to maximise benefits is critical  
517 and therefore requires further research. Nevertheless, Kettlewell et al. (2010)

518 established that crop development stages most sensitive to water stress dictate  
519 timing of di-1-*p*-menthene application for optimum benefits.

520 Following the work of Kettlewell et al. (2010) on the role of crop development  
521 stage, other researchers have found corroborative evidence. Kettlewell and  
522 Holloway (2010) applied di-1-*p*-menthene at the boots swollen stage, GS45, and  
523 found that it improved yield of droughted wheat by as much as 42% compared  
524 with droughted-and-unsprayed plants. In a separate study involving two water  
525 treatments and two GS, Abdullah et al. (2015) observed 30% more wheat grain  
526 yield in droughted plants treated with di-1-*p*-menthene at the booting stage than in  
527 the droughted but unsprayed plants, while application at anthesis had no  
528 significant effect on yield. Recently, Faralli et al. (2017) reported 22% yield  
529 improvement in oil seed rape plants treated with film-forming AT as floral initiation  
530 was taking place but with no improvement from applications at initiation of seed  
531 development. These findings during the last decade are a refutation of earlier  
532 research in terms of ameliorative effects of ATs on droughted crops.

533 Though in part, the mechanisms by which metabolic and reflective ATs ameliorate  
534 drought are better understood than those of film-forming types. However,  
535 discrepancies between researchers indicate the need for more research. As Gale  
536 and Hagan (1966) indicated, this may be attributed to ambient, edaphic and plant  
537 factors such as wind speed, soil water status and turgor of cells, respectively,  
538 prevailing at and after AT application - necessitating the need for researchers to  
539 provide sufficient details in these areas. In spite of our knowledge that di-1-*p*-  
540 menthene applied at the right GS and under drought conditions improves grain  
541 yield, the underlying physiological mechanisms by which this compound  
542 ameliorates drought beyond blockage of stomata are unknown. A study by

543 Weerasinghe et al. (2016) attributed wheat grain yield improvement under drought  
544 conditions using di-1-*p*-menthene to increasing of pollen viability, via increased  
545 plant water conservation. Nevertheless, the discovery of this relationship was only  
546 correlative and not a conclusive cause-and-effect one. Thus, the underlying  
547 mechanisms by which di-1-*p*-menthene improves reproductive development - be  
548 they hormonal or metabolic or otherwise - are yet to be established. In a drought  
549 stressed oil seed rape study by Faralli et al. (2016), a four-fold decrease in  
550 endogenous ABA concentration following an application of di-1-*p*-menthene was  
551 correlated with a 17% yield improvement. This suggests that the drought  
552 amelioration effects of di-1-*p*-menthene may be related to increased catabolism  
553 and/or reduced biosynthesis of ABA. Increased ABA concentration is known to  
554 repress cell wall invertase (CWIN) via down-regulation of genes controlling the  
555 synthesis of this enzyme (Ji et al., 2010; Koonjul et al., 2005). The significance of  
556 CWIN to reproductive development lies in their hydrolysis of sucrose into glucose  
557 and fructose required by anthers and ovaries (Braun et al., 2014; Ruan et al.,  
558 2010). Researching the effects of ATs on ABA signalling with respect to CWIN is  
559 therefore required. Knowledge of mechanisms, if established, could further feed  
560 into developing relevant plant breeding and agronomic management strategies for  
561 improving WUE and crop production.

## 562 **6.0 Challenges in using antitranspirants and other research gaps**

563  
564 There are other research gaps in the use of ATs that need addressing besides  
565 those identified above and in the conclusion. This review has shown that the  
566 effects of ATs on crop development are modulated by prevailing environmental  
567 conditions and intraspecific and interspecific factors. This accounts for apparently



568 contradictory findings by different researchers, hence the need for thorough  
569 description of experimental conditions and materials used. The use of biostimulant  
570 ATs such as fulvic acid will be particularly necessary due to their heterogenous  
571 nature. The type of AT used in research also modulates plant response.  
572 Concerning the effect on leaf temperature, Gale and Hagan (1966) downplayed  
573 the risk of overheating due to AT use (Section 3.3). However, global warming is  
574 likely to increase the risk of heat stress. This may see film-forming ATs play a  
575 minor role than the reflective types that attenuate solar radiation, thereby reducing  
576 the heat load on the leaf.

577 Due to suppressing both transpiration and photosynthesis, ATs reduce not only  
578 the uptake of minerals from the soil but also carbon assimilation. The negative  
579 effect can be minimised by selecting appropriate ATs for a given drought scenario.  
580 Metabolic ATs would be ideal in situations where a dry spell which coincides with  
581 the most drought-sensitive crop growth stage is expected, while film-forming types  
582 would suit prolonged drought events as they have longer-lasting effects (30 to 40  
583 days, Plaut et al., 2004). Nevertheless, finding a product that is more permeable to  
584 CO<sub>2</sub> than water vapour has been a long standing AT challenge yet to be  
585 addressed. Product research is therefore needed to find suitable ATs. Further,  
586 ATs may not be used as a sole drought mitigation technique. However, most if not  
587 all current research focuses on ATs in isolation. An integrated approach is  
588 required, for example, De *et al.* (1983) demonstrated reduced irrigation  
589 requirement in wheat by using combinations of rice stubble and kaolin. Agarwal  
590 (1979) obtained the highest barley yield under a combined stubble mulch-and-  
591 kaolin treatment.

592 The environmental risks associated with the use of the three most popular ATs,  
593 ABA, di-1-*p*-methene and kaolin are likely very low. ABA can be extracted from  
594 plants, obtained through microbial fermentation or synthesised (Shi et al., 2017),  
595 while di-1-*p*-methene is extracted from pine resin (Francini et al., 2011). Kaolin, an  
596 aluminosilicate,  $\text{Al}_4\text{Si}_4\text{O}_{10}(\text{OH})_8$ , is obtained from clay (Cantore *et al.* 2009).  
597 However, kaolin is also used to control insect pests, and studies have  
598 demonstrated that it is effective (Table 2) against some studied species.  
599 Unfortunately, almost all papers reviewed in this article focussed on plant  
600 response to ATs, neglecting the potential negative effects on the environment.  
601 One exception is Pascual et al., 2010 who showed that while kaolin significantly  
602 reduced the incidence of fruit fly (*Bactrocera oleae*) and black scale (*Saissetia*  
603 *oleae*), pests of olives, the AT also caused mortality of their natural enemies (e.g.  
604 coccinellids or ladybird beetles: *Scymnus mediterraneus* and *Stethorus punctillum*,  
605 among other families of natural enemies). Earlier, Marko et al. (2008) established  
606 that severity of infestation with a number of apple pests (e.g. leaf miner moth and  
607 woolly apple aphid) was linked to the use of kaolin. The AT was toxic not only to  
608 pests but also their natural enemies (e.g. spiders and common black ants). More  
609 research is therefore required to establish off-target effects of other ATs,  
610 particularly in this class and in other crops, and how the products can be made  
611 safe.

612 Lack of cost-benefit analysis: Clearer, evidence-based messages on the economic  
613 feasibility of using ATs in crops production, especially in arable farming, are  
614 needed to help prospective adopters make firm decisions. However, the number of  
615 research papers with information on the cost-benefit analysis of using ATs in crop  
616 production is meagre (e.g. Kettlewell, 2011 and Brahma et al., 2007). This is not

617 surprising since yield improvement has been the primary focus of most  
618 researchers. Yield loss due to drought needs to be quantified and valued; and the  
619 yield benefit due to AT application demonstrated in monetary terms. Lack of  
620 thorough, in-depth analyses on the cost-effectiveness of ATs in most crops may  
621 partly be blamed for the erratic response of crop producers in the adoption of ATs  
622 as a drought mitigation option in arable farming. This might also have stifled  
623 research in novel products that could be cheaper.

624 An examination of research findings in Table 2 shows that there has been a  
625 number of studies on nutritional aspects of fruit, particularly involving ABA and  
626 kaolin ATs. Except for two studies on arable crops, the rest of the research on  
627 nutritional effects of ATs were on horticultural crops. This may be attributed to the  
628 fact that most of the studies involving AT products have been on horticulture  
629 (Table 2).

## 630 **7.0 Conclusion and future prospects**

631

632 The agronomic benefits of ATs have been highlighted in this review. ATs improve  
633 yield, conserve irrigation water and also reduce disease and insect pest  
634 incidences. The physiological mechanisms by which metabolic and reflective ATs  
635 ameliorate drought have been described but exactly how they affect reproductive  
636 processes is still unknown. Similarly, although timing of AT application was studied  
637 using the film-forming product, di-1-*p*-menthene, the mode of action of this class of  
638 ATs is yet to be established. The discovery of the role of crop GS in modulating  
639 AT efficacy in wheat by Kettlewell et al. (2010) has been a major research

640 breakthrough of the last decade. This might be the reason behind the increasing  
641 interest in AT research besides the threat of increasing frequency of droughts.

642 As the findings of Kettlewell et al. (2010) were based on a film-forming AT, there is  
643 need for a comparative study involving all the three classes to determine the most  
644 effective types. It would also be interesting to examine interspecific responses to  
645 the AT classes. Discrepancies in plant response suggest that species, genotype,  
646 environment, chemical nature and rate of AT applied further modulate the efficacy  
647 of ATs. In wheat and oil seed rape, film-forming di-1-*p*-menthene has shown  
648 consistent positive results in different growth environments. Further research  
649 opportunities include understanding possible interaction between ATs and heat  
650 stress, testing the efficacy of vegetable oils and integrating ATs with other drought  
651 management techniques (e.g. mulching or cover crops). The broader  
652 environmental impacts of different types of AT must also be considered. Finally,  
653 one of the challenges against achieving world food security ahead of 2050 is not  
654 just finding effective drought amelioration techniques but also increasing the  
655 knowledge and accessibility to the end users of the technologies. ATs are yet to  
656 enter drought amelioration in arable crop production, despite research providing  
657 empirical evidence of agronomic benefits. ATs may still be too expensive for use  
658 in low value crop production systems hence the need to find cheaper alternatives.  
659 Increasing frequency and intensity of droughts and the associated crop failure  
660 may stimulate farmers' adoption of ATs for a role in arable crop production.

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673 Table 1: Examples of the main antitranspirant compounds and their modes of  
674 action in the surveyed literature between 2009 and 2019.

Antitranspirant classes	Compounds	References
Metabolic	s-ABA	Park <i>et al.</i> 2016
	Chitosan (poly (D-glucosamine))	Li, Zhang, <i>et al.</i> 2017; Rieger <i>et al.</i> 2016
	Fulvic acid	Zhang <i>et al.</i> 2016
Reflective	Aluminosilicate (kaolin)	Cantore <i>et al.</i> 2009
	Calcium carbonate (CaCO <sub>3</sub> )	da Silva <i>et al.</i> 2019
	Calcium oxide (CaO)	da Silva <i>et al.</i> 2019

Film-forming	di-1- <i>p</i> -menthene	AbdAllah <i>et al.</i> (2019)
	poly-1- <i>p</i> -menthene	Faralli <i>et al.</i> (2016)
	Acrylic polymers	AgroBest Australia (2017)

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680 Table 2: Summary of antitranspirant research based on 173 peer review articles published between 2009 and 2018.

Year	Antitranspirant class	Antitranspirant product	Research area/objective	Crop/plant species	Some of the reported effects on crop/plant performance	Citation
2009	Reflective	Kaolin	Drought and heat stress	Tomato	Reduced drought and heat stress and improved marketable yield by 21%	Cantore et al., 2009
2009	Reflective	Kaolin	Heat stress management	Apple	Reduced heat stress, increased carbon fixation and fruit size	Glenn, 2009
2010	Reflective	Kaolin	Fruit protection from sunburn	Apple	Increased light reflectance and leaf expansion, reduced sunburn, increased fruit weight and yield	Aly et al., 2010
2010	Reflective	Kaolin	Water stress	Apple	Increased photosynthesis, reduced WUE	Glenn, 2010
2010	Reflective	Kaolin	Insect pest control	Olives	Significant mortality of pests <i>Bactrocera oleae</i> and <i>Saissetia oleae</i> and natural enemies (e.g. <i>Scymnus mediterraneus</i> ).	Pascual et al., 2010
2010	Reflective	Kaolin	Insect pest control	Cotton	Reduced oviposition and egg number of bollworms, <i>Helicoverpa armigera</i>	Alavo et al., 2010
2010	Reflective	Kaolin	Physiological responses	Grapes	Reduced leaf temperature and stomatal conductance but increased leaf water potential under well-watered conditions	Michael Glenn et al., 2010
2010	Reflective	Kaolin	Drought stress	Olives	Maintained plant water status, increased canopy biomass, did not improve chlorophyll content and fruit yield	Roussos et al., 2010
2010	Reflective	Kaolin	Protection from sunburn	Pomegranate	Reduced sunburn damage, no effect on phenolic compounds and antioxidant activity	Weerakkody et al., 2010
2011	Reflective	Kaolin	Insect (Medfly)	Nectarines and	Decreased landing of the pest and	D'Aquino et al.,

			control	peaches	fruit damage	2011
2012	Reflective	Kaolin	Drought stress	Olives	Increased photosynthesis, plant water content, leaf tissue density and reduced leaf temperature	Denaxa et al., 2012
2012	Reflective	Kaolin	Drought stress	Tomato	Improved WUE (by 43%) and increased total biomass and economic yield	Lukic et al., 2012
2012	Reflective	Kaolin plus deficit irrigation	Irrigation management	Grapes	Increased terpene alcohols and anthocyanins, negligible effect on volatile compounds	Song et al., 2012
2012	Reflective	Kaolin, calcium carbonate	Control of cherry fruit fly	Sweet cherry	Kaolin more effective than calcium carbonate in decreasing landing and oviposition and also with higher mortality rates	Yee, 2012
2012	Reflective	Kaolin, magnesium carbonate	Drought stress	Jatropha	Increased relative water content, reduced osmotic pressure and carbohydrate content	Khalil et al., 2012
2012	Reflective	Kaolin	Irrigation management	Strawberry	Reduced irrigation frequency, saved 20% of water required, increased fruit weight	Santos et al., 2012
2013	Reflective	Kaolin	Drought and heat stress	Mango	Reduced irradiance and leaf temperature and improved stomata conductance and photosynthesis. Increased fruit number and yield by 41 and 44%, respectively	Chamchaiyaporn et al., 2013
2013	Reflective	Kaolin, magnesium carbonate	Drought stress	Wheat	Improved photosynthetic pigments, increased yield	Desoky et al., 2013
2013	Reflective	Kaolin	Aphid control	Wheat	Reduced damage, improved biomass and grain yields	Nateghi et al., 2013
2013	Reflective	Kaolin	Drought stress	Soyabeans	Increased yield components, biomass and grain yield	Javan et al., 2013



2013	Reflective	Kaolin	Boll weevil ( <i>Anthonomus grandis</i> ) control	Cotton	Reduced oviposition and boll damage	Silva and Ramalho, 2013
2013	Reflective	Kaolin	Drought stress	Pistachio	Increased fresh weight and soluble solids, reduced early nut splitting	Azizi et al., 2013
2013	Reflective	Kaolin and calcium carbonate	Drought stress	Banana	Reduced irrigation frequency, improved crop productivity	El-Khawaga, 2013
2013	Reflective	Calcium carbonate	Fruit protection from sunburn	Grapes	Chlorophyll and carotenoid enhancement, berry setting and yield improvement	Ahmed et al., 2013
2013	Reflective	Calcium carbonate	Control of potato psyllid ( <i>Bactericera cockerelli</i> )	Irish potatoes	Reduced oviposition, no effect on mortality	Prager et al., 2013
2013	Reflective	Kaolin	Drought stress	Grapes	Reduced stomatal conductance and temperature, increased anthocyanin and phenolics content and berry fresh weight	Shellie and King, 2013
2014	Reflective	Kaolin	Insect pest and disease control	Wheat	Decreased reproduction of beetle, <i>Rhizopertha dominica</i> , reduced multiplication of yeast moulds	Campolo et al., 2014
2014	Reflective	Kaolin plus other materials	Drought stress	Wheat	Improved yield components and yield	Patil et al., 2014
2014	Reflective	Kaolin	Heat stress	Grapes	Increased photosynthesis, transpiration, total soluble solids, berry weight, diameter and improved yield by 44%.	Tepkaew et al., 2014
2015	Reflective	Kaolin	Fruit quality enhancement	Grapes	Effective in reducing leaf temperature through reflectance, did not significantly decrease gas exchange variables, reduced fruit	Lobos et al., 2015

					damage, no effect on fruit nutritional quality	
2015	Reflective	Kaolin	Irrigation management	Bananas	Decreased transpiration rate and amount of irrigation water, increased yield	Gawad, 2015
2015	Reflective	Kaolin	Drought stress	Gooseberry	Reduced transpiration, leaf temperature, improved stem elongation, total biomass and WUE	Segura-Monroy et al., 2015
2015	Reflective	Kaolin	Irrigation water management	Oil seed rape	Reduced irrigation frequency	Badukale et al., 2015
2015	Reflective	Kaolin	Drought stress, transplant survival	Citrus, beans	Decreased transplant shock, improved biomass	Boari et al., 2015
2015	Reflective	Kaolin	Irrigation water management	Egg plant	Reduced irrigation water by 33%, increased chlorophyll content, fruit weight, nutritional quality, plant biomass and economic yield	El-Said, 2015
2015	Reflective	Kaolin	Drought stress and fruit quality	Olives	Enhanced chlorophyll and carotenoid contents, increased oleic acid in olive oil	Khaleghi et al., 2015
2015	Reflective	Kaolin	Heat and drought stress	Grapes	Higher accumulation of active photosystem II reaction centres, lowered mesophyll limitations, increased net photosynthesis, reduced sunburn, improved yield	Correia et al., 2015
2015	Reflective	Kaolin and calcium carbonate	Fruit protection from sunburn	Pomegranate	Reduced sunburn, increased anthocyanin and total sugar content, fruit weight and yield	El-wafa, 2015
2015	Reflective	Potassium silicate	Drought stress	Tomato	Increased relative water content, leaf expansion, WUE, plant biomass and yield	El-azm and Youssef, 2015

2015	Reflective	Kaolin	Pest (whitefly) control	Beans	Reduced the number of eggs, nymphs and adult insects by 70, 75 and 80%, respectively. Suppressed transpiration by 40%, increased chlorophyll content by 43%	Nunez-Lopez et al., 2015
2015	Reflective	Kaolin	Drought stress	Peruvian Ground Cherry	Reduced transpiration, leaf temperature, leaf thickness and trichome density, increased WUE, stem elongation and biomass yield	Segura-Monroy et al., 2015
2016	Reflective	Kaolin	Drought stress and fruit quality	Grapes	Improved intrinsic WUE and anthocyanin content	Brillante et al., 2016
2016	Reflective	Kaolin	Salinity tolerance	Tomato	Mitigated salinity stress and reduced damage by insects: increased marketable yield and reduced sunburn by 17.7 and 76.4%, respectively,	Boari et al., 2016
2016	Reflective	Kaolin	Drought stress	Tomato	Improved WUE, increased individual fruit weight and total yield by 27%	Djurovic et al., 2016
2016	Reflective	Kaolin	Drought stress and fruit quality	Grapes	Enhanced flavonoid and anthocyanin contents	Conde et al., 2016
2016	Reflective	Kaolin	Drought stress	Tomato and pepper	Did not affect stomatal conductance and plant water status significantly	Cosic et al., 2016
2016	Reflective	Kaolin	Drought and heat stress; and fruit quality	Grapes	Increased phenol, flavonoid anthocyanin and vitamin C contents by 40, 24, 32 and 12%, respectively, reduced reactive oxygen species and improving fruit quality	Dinis et al., 2016
2016	Reflective	Kaolin	Heat stress mitigation	Apples	Reduced photosynthetically active radiation interception, increased fruit weight	Glenn, 2016

2016	Reflective	Kaolin	WUE	Apples	Reduced WUE, increased stomatal conductance and transpiration, improved yield	Glenn, 2016b
2017	Reflective	Kaolin	Fruit protection from sunburn	Grapes	Reduced sunburn	Ferrari et al., 2017
2017	Reflective	Kaolin	Control of leafhopper	Grapes	Effective in inducing mortality of nymphs	Tacoli et al., 2017
2017	Reflective	Kaolin	Control of leafhopper	Grapes	Caused mortality of nymphs through inhibition of feeding; and reduced leaf symptoms and damage	Tacoli et al., 2017b
2017	Reflective	Magnesium carbonate, sodium carbonate, potassium nitrate	Drought stress	Soyabeans	Magnesium carbonate and potassium nitrate improved grain yield and protein content	Dass and Bhattacharyya, 2017
2017	Reflective	Kaolin, calcium carbonate (with conservation tillage)	Insect (thrips) control	Cotton and groundnuts	Increased incidence of thrips ( <i>Frankliniella fusca</i> ) in cotton, decreased incidence of tomato spotted wilt virus in groundnuts. No effect on yield in both crops	Knight et al., 2017
2017	Reflective	Potassium nitrate, sodium carbonate and magnesium carbonate	Drought stress	Soyabeans	Increased relative water content, and total biomass and grain yield	Sanbagavalli et al., 2017
2017	Reflective	Kaolin, calcium carbonate	Fruit protection from sunburn	Pomegranate	Reduced sunburn damage, enhanced total soluble solids	Abdel-Sattar et al., 2017
2017	Reflective	Kaolin	Irrigation management	Aubergine	Reduced irrigation frequency and water use, increased yield	Abd El-Hady and Doklega, 2017
2017	Reflective	Kaolin	Light extinction coefficient and radiation use	Pistachio	Reduced single leaf light interception but increased canopy absorbance, light extinction	Vatandoost et al., 2017

			efficiency		coefficient ( <i>K</i> ) not significantly affected, improved light use efficiency in some cultivars	
2018	Reflective	Kaolin	Drought stress	Olives	Maintained leaf water status, improved photosynthesis, ameliorated oxidative damage, whole-plant WUE and biomass not improved	Brito et al., 2018
2018	Reflective	Kaolin	Irrigation and heat stress management	Pepper	Water deficit with kaolin reduced canopy temperature, full irrigation with kaolin increased temperature	Cosic et al., 2018
2018	Reflective	Kaolin	Heat stress	Walnut	Decreased heat stress, enhanced photosynthesis, gas exchange and WUE	Gharaghani et al., 2018
2018	Reflective	Kaolin	Pest ( <i>Diaphorina citri</i> ) control	Citrus	Reduction in host apparency (40%) and recognition (50%)	Miranda et al., 2018
2018	Reflective	Kaolin	Heat stress and fruit quality	Grapes	Enhanced contents of phenolic compounds and anthocyanins	Kok and Bal, 2018
2018	Reflective	Kaolin, calcium carbonate	Pest ( <i>Diaphorina citri</i> ) control	Citrus	Decreased photosynthesis (25%), leaf temperature, incidence of imagoes, nymphs and egg laying	Ramírez-Godoy et al., 2018
2018	Reflective	Kaolin	Fruit protection from sunburn and cracking	Pomegranates	Decreased sunburn (47%) and fruit cracking (46%), increased anthocyanins and phenolic contents and antioxidant activity	Sharma et al., 2018
2018	Reflective	Kaolin	Drought stress	Sunflower	Increased chlorophyll and proline contents, reduced stomatal conductance and transpiration, improved relative water content and yield	El Mantawy and El Bialy, 2018
2018	Reflective	Kaolin	Drought stress	Grapes	Enhanced stomatal conductance, photosynthesis and intrinsic WUE, reduced ABA concentration,	Dinis et al., 2018

					enhanced drought tolerance.	
2018	Reflective	Kaolin	Drought stress	Tomato	Reduced canopy temperature, irrigation water required, net CO <sub>2</sub> assimilation rate and marketable yield	AbdAllah et al., 2018
2018	Reflective	Calcium carbonate	Drought stress	Tomato	Reduced transpiration (by 47 - 58%) and leaf temperature, improved vitamin C and total phenols contents by 15 and 12% respectively, increased antioxidant activity and marketable yield	Patane et al., 2018
2018	Reflective	Kaolin	Irrigation management	Maize	Increased leaf number and plant height, improved biomass accumulation	Ulameer and Ahmed, 2018
2018	Reflective	Kaolin	Graft survival	Mango	Depressed transpiration, enhanced photosynthesis, increased relative water content and survival of grafts	Thorat et al., 2018
2018	Reflective	Kaolin	Drought stress	Pears	Reduced irrigation water applied, elevated indoleacetic acid and gibberellic acid activities	Fayed et al., 2018
2018	Reflective	Kaolin (deficit irrigation; mulch)	Irrigation management	Common Zinnia	Increased plant height and biomass accumulation	El-Deen et al., 2018
2009	Metabolic	ABA	Fruit quality enhancement	Grapes	Increased anthocyanin content, reduced fruit firmness, no effect on soluble solids content, titratable acidity, and berry size	Lurie et al., 2009
2009	Metabolic	Chitosan	Drought stress	Beans	Depressed stomatal conductance – reduced transpiration and photosynthesis, mode of action mediated by ABA, elevated endogenous ABA concentration threefold, no effect on intrinsic WUE	Iriti et al., 2009

2009	Metabolic	ABA	Fruit ripening	Grapes	Promoted fruit ripening and increased berry size	Wheeler et al., 2009
2009	Metabolic	ABA	Vase life extension	Eustoma flowers	Reduced leaf damage attributed to sucrose solution, slowed loss of fresh weight, extended vase life	Shimizu-Yumoto and Ichimura, 2009
2010	Metabolic	ABA	Drought stress	Various woody ornamentals	Reduced stomatal conductance and cumulative water loss, increased stem water potential, extended marketability by one to seven days	Hebert et al., 2010
2010	Metabolic	Chitosan	Drought stress	Bean	Reduced stomatal conductance and transpiration	Ludwig et al., 2010
2010	Metabolic	ABA	Vase life extension	Cut roses	Pre-treatment with ABA did not increase vase life but reduced electrolyte leakage	Pompodakis et al., 2010
2010	Metabolic	ABA	Drought stress	Pansy and Viola	Induced leaf chlorosis, improved drought tolerance by delaying wilting and maintained marketable quality in the presence of benzyladenine and gibberellic acid	Waterland et al., 2010
2010	Metabolic	ABA	Drought stress	Seed Geranium, petunia, marigold and others	Reduced water loss, induced chlorosis, delayed wilting by 1.7 to 4.3 days	Waterland et al., 2010a
2010	Metabolic	ABA	Drought stress	Chrysanthemums	Suppressed stomatal conductance, delayed wilting by 1.2 to 4.0 days, induced recovery from severe drought	Waterland et al., 2010c
2011	Metabolic	Salicylic acid	Vase life extension	Cut roses	Enhanced uptake of vase solution increasing relative fresh weight of flowers, improved antioxidant activities of catalase, extending the vase life	Alaey et al., 2011

2011	Metabolic	ABA	Extension of shelf life	Tomato	Decreased transpiration, stomatal conductance, photosynthesis and irrigation water use. Increased shelf life	Astacio and van Iersel, 2011
2011	Metabolic	ABA	Drought stress	Apples	Enhanced water potential by 62% and reduced endogenous leaf ABA by 45%.	Tworkoski et al., 2011
2011	Metabolic	ABA	Cold tolerance	Citrus	Reduced electrolyte leakage	Yang et al., 2011
2011	Metabolic	Fulvic acid	Drought stress	Maize	Maintained chlorophyll content and gas exchange, enhanced plant growth and yield	Anjum et al., 2011
2011	Metabolic	Chitosan	Disease control	Grapes	Reduced powdery mildew infestation, upregulated polyphenol content and removal of free radicals	Iriti et al., 2011
2011	Metabolic	ABA	Fruit quality enhancement	Grapes	Increased anthocyanin content up to 85%, marginal improvement of total soluble solids contents	Gu et al., 2011
2011	Metabolic	ABA	Drought stress	Smoke bush	Elevated endogenous ABA, did not increase relative water content, reduced stomatal conductance, transpiration and photosynthesis, improved drought tolerance	Li et al., 2011
2011	Metabolic	Salicylic acid	Salt stress	Sunflower	Promoted plant growth, chlorophyll and calcium contents and improved leaf turgor	Noreen et al., 2011
2011	Metabolic	ABA	Fruit quality enhancement	Grapes	Upregulated antioxidant activities by 38%, increased anthocyanins and phenolic contents	Sandhu et al., 2011
2011	Metabolic	ABA	Cold tolerance	Grapes	Effective in inducing leaf senescence, abscission and shoot dormancy and promoting freeze tolerance	Zhang et al., 2011



2011	Metabolic	ABA	Vase life extension	Iris flowers	Prevented flag petal expansion, induced ethylene-independent senescence, upregulating proteolytic degradation and electrolyte leakage	Zhong and Ciafre, 2011
2012	Metabolic	ABA	Cold tolerance	Grapes	Enhanced shoot dormancy and freeze tolerance	Zhang and Dami, 2012
2013	Metabolic	ABA	Fruit ripening	Cucumber	Effective in promoting fruit ripening	Wang et al., 2013
2013	Metabolic	ABA	Flowering regulation	Litchi	Increased flowering per panicle	Cui et al., 2013
2013	Metabolic	Fulvic acid	Drought stress	Wheat	Improved photosynthetic pigments, increased yield	Desoky et al., 2013
2013	Metabolic	Chitosan	Drought stress	Soyabeans	Increased yield components, biomass and grain yield	Javan et al., 2013
2013	Metabolic	Salicylic acid and acetylsalicylic acid	Drought stress	Fibrous flax.	Enhanced stem elongation and fibre yield	Heller et al., 2013
2014	Metabolic	ABA	Fruit quality enhancement	Tomato	Increased both chlorophyll and carotenoid contents in leaf and fruit tissue	Barickman et al., 2014
2014	Metabolic	ABA	Control of blossom end-rot	Tomato	Improved uptake of calcium and reduced blossom end-rot	Casey Barickman et al., 2014
2014	Metabolic	ABA	Vase life extension	Gladiolus	Reduced water uptake, fresh weight, enhanced senescence in cut flowers, decreased vase life by two days	Kumar et al., 2014
2014	Metabolic	ABA (used with ABA Analog: (+)-8'-acetylene ABA)	Fruit set control and gas exchange	Apples	Reduced stomatal conductance and photosynthesis inducing a decline in fruit set	McArtney et al., 2014
2014	Metabolic	Chitosan	Drought stress	Pomegranate	Decreased sugar and anthocyanin contents, increased fruit set, weight and yield	El-Khawaga and Mansour, 2014

2014	Metabolic	ABA	Fruit quality enhancement	Citrus	Increased fruit size and weight, enhanced potassium content, reduced sugar accumulation	Kawai et al., 2014
2014	Metabolic	ABA	Fruit quality enhancement	Grapes	No effect on cluster size or weight, increased anthocyanin polyphenolic compounds	Koyama et al., 2014
2014	Metabolic	ABA	Protection from sunburn	Apples	No effect on sunburn, significantly reduced fruit size and weight and total soluble solids	Mupambi et al., 2014
2014	Metabolic	ABA	Transplant shock	Leafy vegetables	Improved quality of seedlings pre-planting, increased marketability of spinach at harvest	Racsko et al., 2014
2014	Metabolic	ABA	Transplant shock	Artichoke	Induced stomatal closure, increased plant water potential, reduced electrolyte leakage, enhanced drought tolerance	Shinohara and Leskovar, 2014
2014	Metabolic	ABA	Drought stress	Pansies	Decreased leaf chlorophyll content, stomatal conductance and carbon assimilation, induced chlorosis.	Weaver and van Iersel, 2014
2015	Metabolic	ABA	Vase life extension	Lilium Sorbonne	Increased sucrose uptake from solution, contents of simple sugars and fresh weight	Geng et al., 2015
2015	Metabolic	ABA	Cold tolerance	Grapes	Enhanced cold tolerance, did not have an effect on yield and berry quality, no evidence of toxicity	Dami et al., 2015
2015	Metabolic	ABA	Fruit quality enhancement	Grapes	Increased anthocyanin content, antioxidant activity and bunch yield	Ferrara et al., 2015
2015	Metabolic	ABA	Fruit quality enhancement	Grapes	Increased anthocyanins content and improved flavour of juice	Yamamoto et al., 2015
2015	Metabolic	Fulvic acid	Drought stress	Tomato	Improved relative water content and marketable yield by 24%, irrigation WUE by 34.82%.	Aggag et al., 2015

2015	Metabolic	Fulvic acid	Drought stress	Oil seed rape	Enhanced maximum quantum efficiency of photosystem II, fluorescence of chlorophyll a, antioxidant activities, ameliorated lipid peroxidation.	Lotfi et al., 2015
2016	Metabolic	ABA	Drought stress	Apple	Depressed gas exchange variables, water deficit stress not alleviated	Al-Absi and Archbold, 2016
2016	Metabolic	ABA	Cold stress	Blueberry	Reduced electrolyte leakage of floral parts increasing their tolerance to freezing injury	Panicker and Matta, 2016
2016	Metabolic	ABA	Cold stress	Grapes	Reduced bud damage	Bowen et al., 2016
2016	Metabolic	Acetylsalicylic acid	Vase life extension	Cut roses	Reduced transpiration, extended vase life	Fanourakis et al., 2016
2016	Metabolic	ABA	Cold stress and fruit quality	Grapes	Induced early leaf senescence, abscission, enhanced dormancy, increased cold tolerance	Li and Dami, 2016
2016	Metabolic	ABA	Fruit quality enhancement	Grapes	Upregulated flavonoid and anthocyanin biosynthesis genes, increased anthocyanin content	Katayama-Ikegami et al., 2016
2016	Metabolic	ABA	Drought stress	Various bedding plants	Depressed stomatal conductance, improved drought tolerance by delaying wilting by between 1.3 and 3.7 days	Park et al., 2016
2016	Metabolic	ABA	Fruit quality enhancement	Grapes	Improved berry and bunch sizes, total soluble solids and fruit firmness	Singh et al., 2016
2016	Metabolic	Fulvic acid	Water deficit conditions	Wheat	Improved WUE, carbon assimilation and yield	Zhang et al., 2016
2016	Metabolic	ABA	Water deficit conditions	Grapes	Reduced electrolyte leakage and lipid peroxidation, improved antioxidant activity	Wang et al., 2016
2016	Metabolic	ABA	Water deficit	Wheat	Improved WUE and yield	Zhang et al., 2016

2017	Metabolic	ABA	Fruit thinning	Pears	Suppression of net photosynthesis by 75-90%, increased fruit size, fruit quality unaffected	Arrington et al., 2017
2017	Metabolic	Salicylic acid, Benzoic acid	Drought stress	Tomato	Increased leaf area index, fruit number and marketable yield	Isa et al., 2017
2017	Metabolic	ABA	Fruit quality enhancement	Tomato	Enhanced the concentrations of fructose, glucose and the contents of chlorophyll and carotenoids	Barickman et al., 2017
2017	Metabolic	ABA	Fruit quality enhancement	Grapes	Elevated accumulation of ethanol, depressed aroma quality	Gonzalez et al., 2018
2017	Metabolic	Salicylic acid	Vase life extension	Cut roses	Sustained membrane stability, attenuated lipid peroxidation, reduced weight loss, enhanced antioxidant activities, extended vase life	Kazemi et al., 2017
2017	Metabolic	Chitosan	Vase life extension	Macaw flower	Increased anthocyanin and flavonoid contents by 48 and 46%, respectively, sustained fresh weight, extended vase life by 10.3 days	Banuelos-Hernandez et al., 2017
2017	Metabolic	ABA	Fruit quality enhancement	Grapes	Enhanced soluble solids, anthocyanin and total phenolic contents	Neto et al., 2017
2017	Metabolic	ABA	Post-harvest preservation	Grapes	Decreased shatter, decay and loss of fruit weight	F. J. D. Neto et al., 2017
2017	Metabolic	ABA	Fruit quality enhancement	Grapes	Upregulated anthocyanin biosynthesis genes, elevated anthocyanins content	Olivares et al., 2017
2017	Metabolic	ABA	Berry and cluster manipulation	Grapes	Reduced berry number, improved berry and cluster uniformity	Padmalatha et al., 2017
2017	Metabolic	ABA	Extension of marketability	Tomato	Inhibited stem elongation, leaf expansion and shoot biomass accumulation by 22% effectively	Agehara and Leskovar, 2017

					prolonging market value	
2017	Metabolic	Chitosan	Drought stress	White clover	Increased contents of amino acids, sugars, sugar alcohols, antioxidants and other metabolites associated with drought resistance mechanisms	Z. Li et al., 2017
2017	Metabolic	Fulvic acid	Crop productivity	Safflower	Improved seed yield by 36% and oil content by 86%	Moradi et al., 2017
2018	Metabolic	ABA	Stomatal physiology	Cut gerberas	Increased percentage of closed stomata, reduced stomatal aperture, decreased water loss	Huang et al., 2018
2018	Metabolic	ABA	Fruit quality enhancement	Grapes	Increased anthocyanin and aroma volatiles contents, decreased fruit firmness	Jia et al., 2018
2018	Metabolic	ABA	Fruit quality enhancement	Grapes	Enhanced phenolic compounds and anthocyanin contents, increased grape yield	Kok and Bal, 2018b
2018	Metabolic	ABA	Fruit quality enhancement	Grapes	Upregulated anthocyanin and flavonoid gene expression	Koyama et al., 2018
2018	Metabolic	ABA	Fruit quality enhancement	Blueberry	Elevated endogenous ABA, increased anthocyanins (malvidin, delphinidin, petunidin glycosides) and fruit softening	Oh et al., 2018
2018	Metabolic	ABA	Fruit quality enhancement	Oranges	Enhanced colour index and carotenoid content, reduced organic acids, no effect on sugar content	Rehman et al., 2018
2018	Metabolic	Chitosan	Drought stress	Wheat	Improved chlorophyll, carotenoid, proline and superoxide dismutase contents	Singh et al., 2018
2018	Metabolic	Chitosan, deficit irrigation	Irrigation management	Wheat	Increased stem extension and leaf expansion	Reddy et al., 2018

2018	Metabolic	Fulvic acid	Low rainfall/drought stress	Maize	Increased kernel number per ear, did not increase yield	Yang et al., 2018
2018	Metabolic	Fulvic acid	Drought stress	Tomato	Reduced canopy temperature, irrigation water required (by 28%), net CO <sub>2</sub> assimilation rate and marketable yield, increased WUE by 33.45%	AbdAllah et al., 2018
2018	Metabolic	Phenyl mercuric acetate	Drought stress	Oil seed rape	Increased plant height and total biomass, but not seed oil and protein contents	Kumar et al., 2018
2009	Film-forming	Di-1- <i>p</i> -menthene	Drought stress	Kiwi fruit	Enhanced efficiency of photosystem II and chlorophyll content, non-significant effect on yield	Latocha et al., 2009
2009	Film-forming	Di-1- <i>p</i> -menthene	Drought stress	Sultani fig	Reduced sugars and total soluble solids, improved vegetative growth and yield	Al-Desouki et al., 2009
2009	Film-forming	Di-1- <i>p</i> -menthene	Physiology, nutrient uptake and yield	Pepper	Suppressed carbon assimilation, reduced water absorption, no effect on cation uptake and dry weight and yield, reduced incidence of blossom-end rot	del Amor and Rubio, 2009
2009	Film-forming	Canola oil (other vegetable oils)	Control of powdery and downy mildews	Cucumber	Reduced powdery and downy mildews by 99 and 96%, respectively	Jee et al., 2009
2009	Film-forming	Di-1- <i>p</i> -menthene, poly-1- <i>p</i> -menthene	Control of apple scab ( <i>Venturia inaequalis</i> )	Apples	Increased chlorophyll fluorescence, decreased conidia germination and foliar and fruit scab severity, improved yield	Percival and Boyle, 2009
2010	Film-forming	Di-1- <i>p</i> -menthene	Drought stress	Wheat	Improved yield at high soil water deficit	Kettlewell et al., 2010

2010	Film-forming	Di-1- <i>p</i> -menthene	Drought stress	Wheat	Improved yield	Kettlewell and Holloway, 2010
2010	Film-forming	Di-1- <i>p</i> -menthene	Drought stress	Bean	Reduced stomatal conductance	Ludwig et al., 2010
2010	Film-forming	Di-1- <i>p</i> -menthene	Drought stress	Pepper	Reduced gas exchange under ambient CO <sub>2</sub> concentration, higher water potential and photosynthesis under combined elevated CO <sub>2</sub> and AT	del Amor et al., 2010
2010	Film-forming	Di-1- <i>p</i> -menthene	Drought stress	Citrus	Non-significant effect on gas exchange, plant water status, chlorophyll and proline contents	Mohawesh et al., 2010
2010	Film-forming	Di-1- <i>p</i> -menthene	Fruit quality control	Grapes	Depressed transpiration and carbon assimilation rates, increased intrinsic WUE and anthocyanin content, reduced yield	Palliotti et al., 2010
2011	Film-forming	Di-1- <i>p</i> -menthene	Ozone stress	Beans	Reduced membrane damage, maintained stomatal conductance and photosynthesis	Francini et al., 2011
2012	Film-forming	Carboxylated hydrophilic polymer (Envy)	Transplant shock	Agarwood	Neither improved growth rates nor reduce stress and mortality of transplants	Page and Awarau, 2012
2013	Film-forming	Castor bean oil	Drought stress	Soyabeans	Increased yield components, biomass and grain yield	Javan et al., 2013
2013	Film-forming	Di-1- <i>p</i> -menthene	Micronutrient and trace element quality	Sweet cherry	No effect on quantity of manganese, nickel, cadmium, copper or zinc	Mikiciuk et al., 2013
2013	Film-forming	Di-1- <i>p</i> -menthene	Control of sugar content	Grapes	Reduced transpiration, photosynthesis, intrinsic WUE, anthocyanin content (by 19%) and sugar content	Palliotti et al., 2013
2014	Film-forming	Di-1- <i>p</i> -menthene	Drought stress	Wheat and barley	Improved water potential in both crops, increased photosynthesis in wheat only	Ouerghi et al., 2014

2015	Film-forming	Di-1- <i>p</i> -menthene	Drought stress	Wheat	Improved plant water status, photosynthesis and yield	Abdullah et al., 2015
2015	Film-forming	Paraffin	Drought stress	Potatoes	Reduced transpiration, improved WUE, total yield and marketable yield	Khalel, A. M. S., 2015
2015	Film-forming	Di-1- <i>p</i> -menthene		Strawberry	Reduced transpiration without depressing carbon assimilation, increased relative water content and WUE, no effect on chlorophyll	Mikiciuk et al., 2015
2016	Film-forming	Di-1- <i>p</i> -menthene	Drought stress	Wheat	Improved water potential, pollen viability and grain yield	Weerasinghe et al., 2016
2016	Film-forming	Poly-1- <i>p</i> -menthene and di-1- <i>p</i> -menthene	Drought stress	Oil seed rape	Decreased endogenous ABA, improved flower and pod water potential.	Faralli et al., 2016
2016	Film-forming	Di-1- <i>p</i> -menthene	Fruit quality	Grapes	No effect on intrinsic WUE, depressed gas exchange, sugar and anthocyanin content	Brillante et al., 2016
2016	Film-forming	Di-1- <i>p</i> -menthene	Controlled ripening	Grapes	Reduced gas exchange, slowed sugar accumulation	Gatti et al., 2016
2017	Film-forming	Poly-1- <i>p</i> -menthene and di-1- <i>p</i> -menthene	Drought stress	Oil seed rape	Reduced transpiration and stomatal conductance, enhanced water potential and yield	Faralli et al., 2017
2017	Film-forming	Di-1- <i>p</i> -menthene	Drought stress	Oil seed rape	Reduced CO <sub>2</sub> assimilation and relative water content, increased intrinsic WUE	M. Faralli et al., 2017
2018	Film-forming	Poly-1- <i>p</i> -menthene	Vase life extension	Roses	Reduced transpiration, increased vase life	Di Stasio et al., 2018
2018	Film-forming	Di-1- <i>p</i> -menthene	Drought stress	Grapes	Reduced both leaf and bunch stomatal conductance, photosynthesis and transpiration, elevated leaf and berry temperature	Fahey and Rogiers, 2018



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683 **Conflicts of Interest**

684 The authors declare no conflicts of interest.

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