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Physiological Effects of Kaolin Particle Film Technology: A Review

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ABSTRACT

Particle film applications (i.e. spraying canopies with a suspension of particles of various kinds of clay, including kaolin, leaving a film on the leaves) has long been used to limit the impact of water and heat stress on crops. Earlier work has focused primarily on crop yield and suggests that particle film applications, in some crops and under some conditions, increases yield. More recent and detailed work has been carried out using new kaolin products. Such work suggests that, besides other effects on fruit colour and size, kaolin generally reduces photosynthetic rates of individual leaves except under high temperature and/or heat stress. This is probably because kaolin films increase the albedo thus reducing leaf temperature and the consequent heat stress, but also reducing the light available for photosynthesis, possibly offsetting benefits of lower temperature, depending on the level of heat stress and incident irradiance. The few studies on the effects of kaolin applications on canopy photosynthesis report either an increase, or no effect, despite a reduction in photosynthetic rates of individual leaves. This is probably due to improved light distribution within the canopy, which increases the radiation use efficiency more than compensating for the slight reduction in canopy light absorption. In conclusion, kaolin applications appear to have the ability to reduce the effects of water and/or heat stress and, possibly to enhance canopy photosynthesis, at least under certain circumstances. These effects alone might not necessarily justify kaolin applications economically. However, when the kaolin film technology is adopted for pest management or for other purposes, it can be concluded that there are possible additional benefits.

Keywords: photosynthesis, stomatal conductance, surround, transpiration, yield

Abbreviations: ***Ø***, apparent quantum yield; Ψ_l, leaf water potential; Ψ_s, stem water potential; A_{max}, light saturated leaf photosynthesis; ***E***, transpiration; g_s, stomatal conductance; ***PAR***, photosynthetically active radiation; ***PhRUE***, radiation use efficiency; *RWC*, leaf relative water content

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INTRODUCTION

Particle film applications (i.e. spraying canopies with a suspension of particles of various kinds of clay, including kaolin, leaving a film on the leaves) have long been used to limit the impact of water and heat stress on crop physiology and productivity. Results have often been inconsistent as such applications resulted at times in increased yield and at other times in no effect or reduction of yield.

Recently, the application of a particular kaolin product (Surround WP, Engelhard, Iselin, N.J.), containing 95% kaolin, was found to be beneficial in pest control on fruit tree species (Glenn *et al*. 1999; Unruh *et al*. 2000; Thomas *et al*. 2004). Kaolin is a naturally occurring mineral (a clay), which main constituent is kaolinite ($Al_2Si_2O_5(OH)_4$). Kaolin applications were also found to be beneficial against certain plant diseases (Puterka *et al*. 2000; Thomas *et al*. 2004), including viruses (Creamer *et al*. 2005) and even to protect plants from frost damage (Wisniewski *et al*. 2002; Walters 2006). Kaolin films were also found, in some cases but not always, to protect crops from sunburn (Glenn *et al*. 2001; Schupp *et al*. 2002; Wand *et al*. 2006), while the effects on fruit colour has been variable (Schupp *et al*. 2002; Glenn *et al*. 2003). Providing details on these results is not in the scope of this review.

Because of these recent findings, a revival of studies aimed at understanding the physiological effects of kaolin applications has occurred with, again, contradictory results. In this review I will summarize the results of several studies concerned with the effect of kaolin applications on the crop

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yield and physiology, particularly the gas exchange and water status at the leaf and the canopy level. In the "Rationale section" I will attempt to provide a general understanding of the physiological effects of kaolin applications that might explain the apparently contradictory results available in the literature.

Kaolin and temperature

Most of the literature is consistent in showing that kaolin applications decrease the temperature of leaves and canopies. For instance, Tworkoski *et al*. (2002) found a significant reduction in the leaf temperature of greenhouse bean leaves from 27.4°C in the leaves of the control plants, to 26.8°C in the leaves of kaolin treated plants, when using a 3% suspension in water and methanol of M96-018 (Engelhard Corporation, Iselin, NJ) kaolin product. Jifon and Syvertsen (2003) found that the leaf temperature of "Ruby Red" grapefruit trees, treated with a 6% kaolin (Surround WP) suspension in water, was about 3°C lower than leaves of control trees during midday, while there was no difference early in the morning and late in the afternoon. Lombardini *et al*. (2004), using the same product on pecan, found a reduction in leaf temperature up to 4°C. Rosati *et al*. (2006) found a 2-3°C reduction, again using a 6% water suspension of Surround WP on walnut and almond. Similar results were obtained by other authors (Abou-Khaled *et al*. 1970; Singh and Sahay 1989; Kadbane and Mungse 1999; Makus 2000; Glenn *et al*. 2001, 2003). In summary, kaolin applications appear to reduce the leaf temperature by about 1-4°C. This reduction is minor compared to the increase in leaf or canopy temperature with water stress. For instance, kaolin applications failed to lower the leaf temperature of water stressed walnut trees to the temperature of the leaves of well irrigated trees (Rosati *et al*. 2006). Additionally, kaolin (i.e. 8.7% Surround WP + surfactant) did not reduce significantly pepper leaf temperature (33.3 and 32.9°C, respectively for control and kaolin treatments) at midday on clear days in Georgia (Russo and Díaz-Pérez 2005). In rare cases, whitening the leaves resulted in increased leaf temperature (Baradas *et al*. 1976).

Kaolin, stomatal conductance, transpiration and water status

The effect of kaolin application on stomatal conductance (g_s) and transpiration (E) has been inconsistent, with few findings reporting increased g_s and/or E. Rao (1985) reported decreased stomatal resistance (i.e. increased conductance) in the fruit developmental stage of tomato plants treated with kaolinite 5% (no further details given), with values ranging for different cultivars from 22.7 to 25.7 s cm^{-1} in the control and from 16.5 to 17.0 s cm^{-1} for the kaolin treated plants. Jifon and Syvertsen (2003) reported reduced midday depression of g_s in grapefruit, during hot days (up to 35 °C) with high incident irradiance (up to 2000 µmol m^{-2} s^{-1}). Under such conditions, g_s was about 0.15 mol m^{-2} s^{-1} for leaves of treated plants and about 0.10 mol m^{-2} s^{-1} for leaves on control plants, the difference being statistically significant. In the morning g_s was higher (between 0.17 and 21 mol m^{-2} s^{-1}) and not different between treatments. Thomas *et al*. (2004), using various amounts of Surround WP in apple found that g_s increased significantly from 40.5 mmol m^{-2} s^{-1} in control leaves up to 64.6 mmol m^{-2} s^{-1} in the most heavily treated plants on 20 July, and from 27 to 57 mmol m^{-2} s^{-1} on 21 August. E increased similarly from 2.39 to 3.68 mmol m^{-2} s^{-1} on 20 July, and from 1.35 to 2.64 mmol m^{-2} s^{-1} on 21 August. These were the two hottest days out of nine measurement days; no significant differences were found on the other days. E was similarly increased in cotton, again using Surround WP (Makus 2000).

Other works reported reductions in g_s and/or E. In water stressed cotton, Moreshet *et al*. (1979) found decreasing g_s with time after kaolin application (i.e. down to 58% of the control) on plants treated with a 25% suspension of fine grade kaolin (speswhite, English China Clay Sales Co. Ltd., St. Austell, England) to which 0.3% sodium hexametaphosphate was added. Tworkoski *et al*. (2002) found reductions in both g_s and E of greenhouse bean leaves: g_s decreased (though not significantly) from 608 to 528 mmol m^{-2} s^{-1}; E decreased significantly from 6.5 to 5.8 mmol m^{-2} s^{-1}. Similar results were found in groundnut (Khan and Morey 1980), onion (Rao and Bhatt 1990) and mungbean (Kadbane and Mungse 1999).

No effect of kaolin application on either g_s or E were found in other works. For instance, Russo and Díaz-Pérez (2005) found g_s values of 220 and 257 mmol m^{-2} s^{-1} and E values of 5.9 and 6.0 mmol m^{-2} s^{-1} respectively for control and kaolin treated plants with no significant differences. In walnut and almond kaolin applications did not affect g_s, which remained at about 0.5 mol m^{-2} s^{-1} for both kaolin and control treatments in almond, and varied from 0.3 to 0.6 mol m^{-2} s^{-1} in irrigated walnut and from 0.2 to 0.02 mol m^{-2} s^{-1} in water stressed walnut, with no difference between kaolin and control trees (Rosati *et al*. 2006). Similar results were obtained in pecan (Lombardini *et al*. 2004), and in apple (Wünsche *et al*. 2004).

Moreshet *et al*. (1979) hypothesized that kaolin particles could block stomata, thus reducing stomatal conductance, but this hypothesis has not been confirmed. Later reports suggest that stomata are not blocked but rather less dense: in chilli (cv. 'Sindhur'), Mahalakshmi *et al*. (1999) found that the number of stomata per square millimeter was reduced from 45 to 19 with a 5% kaolin application. Subramanian *et al*. (1992) found similar results in cotton with a 3% kaolin application. Lower stomatal density might explain why g_s and E are found to decrease in some studies and not in others: it takes some time for new growth to respond to kaolin with decreased stomatal density and consequently decreased g_s and E. When stomatal conductance and transpiration are measured soon after kaolin application, the effect of kaolin cannot involve lower stomatal density and stomatal conductance and transpiration might be less affected if at all.

Plant water status (i.e. leaf, Ψ_l, or stem, Ψ_s, water potential and/or leaf relative water content, *RWC*) was not affected by kaolin in some experiments. In grapefruit Ψ_l did not vary (P = 0.92) between kaolin and control leaves, reaching -1.77 and -1.76 MPa for kaolin and control leaves respectively (Jifon and Syvertsen 2003). In walnut and almond kaolin applications did not affect Ψ_s, which ranged during the day between -0.4 and -0.8 MPa in irrigated almond, between -0.6 and -1.4 MPa in droughted almond, between -0.1 and -0.4 MPa in irrigated walnut and from -0.6 to -1.3 in water stressed walnut, independent of kaolin application (Rosati *et al*. 2006). Similarly, no effect of kaolin on Ψ_s was observed in pecan (Lombardini *et al*. 2004).

Kaolin applications slowed down the decrease in Ψ_l with the onset of drought in water stressed cotton, resulting in higher (less negative) values towards the end of the crop cycle (Moreshet *et al*. 1979). Rao (1985) reported higher Ψ_l with kaolin in the fruit developmental stage of tomato plants, with values ranging for different cultivars from -0.44 to -0.49 MPa in the control and from -0.33 to -0.39 MPa for the kaolin treated plants. In chilli pepper Mahalakshmi *et al*. (1999) found for two seasons that foliar application of 5% kaolin induced higher RWC (80.8 and 83.0%, respectively for the first and second season) compared to controls. Similarly, RWC was improved in *Phaseolus aureus* and *Vigna catiang* (Pawar and Patil 1982) and cotton (Singh and Sahay 1989).

Kaolin and photosynthesis

In some cases kaolin applications were found to improve leaf light-saturated photosynthesis (A_{max}). For instance Glenn *et al*. (2001) found increased A_{max} in apple in seven of the eight trials carried out in Chile and USA. Thomas *et al*. (2004), using various amounts of Surround WP in apple found that A_{max} increased significantly only in the two hottest days (i.e. leaf temperatures of control trees of 38.4 and 40.1°C) out of nine measurement days. A_{max} increased from 8.6 μmol m^{-2} s^{-1} in control leaves up to 14.7 μmol m^{-2} s^{-1} in the most heavily treated plants on 20 July, and from 3.9 to 6.1 μmol m^{-2} s^{-1} on 21 August. In citrus, Jifon and Syvertsen (2003) found increased A_{max} (from about 4 to about 6 μmol m^{-2} s^{-1}) but only at midday under high temperature (not shown) and high leaf-to-air vapour pressure difference (i.e. about 4 kPa in the control). In the morning, A_{max} was about 7-8 μmol m^{-2} s^{-1} and not different between kaolin and control trees.

Other authors found no effect of kaolin applications on photosynthesis. In greenhouse beans Tworkoski *et al.* (2002) found A_{max} values of 17.8 μmol m^{-2} s^{-1} in kaolin treated plants and 17.7 μmol m^{-2} s^{-1} in control plants, with no significant difference. Similarly, Russo and Díaz-Pérez (2005) found no difference in field-grown pepper where A_{max} was 37.6 μmol m^{-2} s^{-1} in the kaolin treatment and 33.1 μmol m^{-2} s^{-1} in the control, with no significant differences, while leaf temperatures were about 33°C for both treatments. Similar results were found in pecan (Lombardini *et al*. 2004).

More often a reduction in A_{max} with kaolin applications has been found. In cotton, Moreshet *et al*. (1979), found decreasing A_{max} with time after kaolin application, down to 76.1% of the control. In walnut and almond, A_{max} was decreased anywhere between 1 and 4 μmol m^{-2} s^{-1}, except in late afternoon in water stressed walnut when A_{max} was as low as 4 μmol m^{-2} s^{-1} (Rosati *et al*. 2006). Similar results have been found in apple by several authors (Schupp *et al*. 2002; Grange *et al*. 2004; Wünsche *et al*. 2004). Most of these authors agree that the decrease in A_{max} is due to the shading effect of kaolin, which reduces the light available for photosynthesis due to the 20 to 40% increased reflecion and decreased absorption with particle films as discussed below. The shading effect of kaolin films on leaves is confirmed by the reduction in the apparent quantum yield (*Ø*) as found by Grange *et al*. (2004) and by Rosati *et al*. (2006). The latter authors showed that kaolin applications reduced *Ø* from 0.05 to 0.03 mol mol^{-1} which implied a 37% decrease in light absorption. Increasing incident photosynthetically active radiation (PAR) well above that of a sunny day, the difference in A_{max} between kaolin treated and a control leaves disappeared.

The effects of kaolin applications on canopy photosynthesis have been rarely measured: Wünsche *et al*. (2004) found that kaolin did not affect canopy photosynthesis despite a reduction in photosynthetic rates of individual leaves. Indeed, Glenn *et al*. (2003) found an increase in canopy photosynthesis under high air temperature.

Kaolin, light reflection and absorption

The ability of kaolin applications to increase the albedo of the vegetation has long been established. Doraiswamy and Rosenberg (1974) found that kaolinite increased total reflection in the visible (380-750 nm) wavelength interval of a soybean canopy by 87-312%, depending on canopy and sky condition and time of day. Kumar *et al*. (1992) found that a reflectant layer of kaolin + detergent + gum adhesive sprayed at 20-d intervals increased crop albedo by 44%.

Khan and Morey (1980) and Pawar and Patil (1982) found similar results respectively in groundnut (*Arachis hypogaea*) and in summer mung (*Phaseolus aureus*) and cowpeas (*Vigna catiang*). Using a spectrophotometer, Wünsche *et al*. (2004) found that the absorption of PAR by apple leaves was reduced by 20%, all of the reduction deriving from increased (+20%) PAR reflection (albedo). Similar results were found in pecan (Cottrell *et al*. 2002). In cotton, leaf absorption was reduced by about 35-40% in the PAR range (Moreshet *et al*. 1979); similarly, in walnut the reduction was 37% for the most heavily coated leaves (Rosati *et al*. 2006). Overall, leaf PAR absorption appears reduced by 20-40% with kaolin applications.

Despite such reduction in PAR absorption at the leaf level, at the canopy level the reduction is lower, ranging in the order of 7% of incident PAR in almond and walnut orchards (Rosati *et al*. 2007) or 8% of global radiation (Doraiswamy and Rosenberg 1974). This implies that a great part of the PAR reflected by the kaolin film at the leaf level is re-intercepted and eventually absorbed within the canopy.

Kaolin and light distribution within the canopy

Little data is available on the effect of kaolin application on light distribution within the canopy. However, early work (Doraiswamy and Rosenberg 1974; Lemeur and Rosenberg 1976) showed that a kaolinite reflectant increased the radiation penetration into a soybean canopy. By placing small PAR sensors on individual leaves, Rosati *et al*. (2007) showed that kaolin application increased light penetration within walnut and almond canopies, resulting in increased incident PAR on inner canopy leaves, compared to non-sprayed trees, even after considering the shading effect of the film.

Kaolin, plant growth and yield

Kaolin application have been often found to increase crop yield. In sorghum Stanhill *et al*. (1976) found that canopy spraying of a 25% kaolin suspension increased average annual yield by 11% over 3 years, the most effective spraying being that applied from 7 weeks after seedling emergence to just before ear emergence. A foliar spray of 6% kaolinite clay suspension applied 45 days after sowing increased yields by 27.7 and 16.5% in a dry and a wet year, respectively, in dryland wheat (De and Giri 1978b). In cotton, Moreshet *et al*. (1979) found a 12% increase in gross yield (from 1830 to 2060 kg ha^{-1}) in one of two years. Also in cotton, Subramanian and Sheriff (1992) found that foliar sprays of 3% kaolin gave average kapas yields of 2.13 t ha^{-1} compared with 1.00 t ha^{-1} in the untreated control while Singh and Sahay (1989), using a 6 or 12% kaolin suspension one month after the cessation of monsoon rains, found cotton yields of 1.79 and 1.89 t ha^{-1}, respectively, compared with 1.68 t ha^{-1} with water spray and 1.66 t ha^{-1} in the untreated control. Similar results were found in rapeseed (De and Giri 1978a), tomato (Rao 1985), peanuts (Khan and Morey 1980; Soundara Rajan *et al*. 1981; Joshi *et al*. 1987), wheat (Dhiman *et al*. 1979; Singh *et al*. 1981), barley (Uppal and Cheema 1981; Solanki *et al*. 1987), sunflower (Jambhale and Thorat 1988), chilli pepper (Mahalakshmi *et al*. 1999), apple (Glenn *et al*. 2001), pear (Puterka *et al*. 2000), *Vigna radiata* (Ingawale *et al*. 1988; Kumar *et al*. 1992), highbush blueberry (Spiers *et al*. 2003), *Polianthes tuberosa* (Al-Moftah 2005), olive (Saour and Makee 2003), *Cyamopsis tetragonoloba* (Sen and Daiya 1983), *Brassica juncea* "Varuna" (Damor and Vegada 1984), pearlmillet (Pandey *et al*. 1988; Kaushik and Gautam 1991).

However, other times the yield was lower or unaffected: "Fuji" apple yielded 32.31 kg per tree with kaolin and 31.46 kg per tree in the control with no significant difference (Schupp *et al*. 2002). Yield of 'Doyenne du Comice' ('Comice') pear were not affected by kaolin (Surround WP) treatment programs consisting of applications at 3 or 6% applied either three or six times per growing season and repeated for three years (Sugar *et al*. 2005). Non significant yield differences were found also in pepper (Russo and Díaz-Pérez 2005). Tworkoski *et al*. (2002) found no significant difference in the yield of greehouse beans, which was 6.7 g per plant with kaolin and 8.4 g in the control.

Similar contradictions were found in plant growth, which was increased in highbush blueberry (Spiers *et al*. 2003) and olive seedlings (Saour 2005), but was unaffected in pear (Sugar *et al*. 2005).

RATIONALE

In the following paragraphs, possible explanations for the different and apparently contrasting results will be discussed.

Kaolin and temperature

The general reduction in leaf and canopy temperature with kaolin (Abou-Khaled *et al.* 1970; Moreshet *et al.* 1979; Singh and Sahay 1989; Kadbane and Mungse 1999; Makus 2000; Glenn 2001; Tworkoski *et al.* 2002; Glenn 2003; Jifon and Syvertsen 2003; Lombardini *et al.* 2004; Rosati *et al.* 2006) can be explained considering the increased albedo (Doraiswamy and Rosenberg 1974; Khan and Morey 1980; Pawar and Patil 1982; Kumar *et al.* 1992; Cottrell *et al.* 2002; Wünsche *et al.* 2004; Rosati *et al.* 2006): since a smaller fraction of the incident radiation is absorbed, the leaves remain cooler than control ones, at least the most sunlit leaves. However, the shade provided by the film often decreases the leaf photosynthesis (Moreshet *et al.* 1979; Schupp *et al.* 2002; Grange *et al.* 2004; Wünsche *et al.* 2004; Rosati *et al.* 2006) and consequently stomatal conductance and transpiration (Moreshet *et al.* 1979; Khan and Morey 1980; Rao 1985, 1986; Rao and Bhatt 1990; Kadbane and Mungse 1999; Tworkoski *et al.* 2002). In rare cases, the decreased transpiration may compensate for the decrease in incident radiation, so that leaf temperature remains similar or even increases as infrequently found (Baradas *et al.* 1976). In most cases, however, transpiration is not reduced enough (if at all) and kaolin coated leaves remain cooler than non-sprayed leaves.

Kaolin, gas exchange and water status

As discussed earlier, the increased albedo with kaolin applications reduce the light available for leaf photosynthesis, thus reducing it. The reduction in leaf photosynthesis often results in a parallel reduction of g_s and E. Lower E is also explained considering the lower leaf temperature with kaolin, which reduces the leaf to air vapour pressure difference, further reducing transpiration at any g_s. Lower E results in better conservation of soil water in non irrigated crops. This explains why most of the experiments where kaolin applications improved yield were carried out on water stressed crops as in sorghum (Stanhill *et al.* 1976) wheat (De and Giri 1978b; Dhiman *et al.* 1979), cotton (Moreshet *et al.* 1979; Singh and Sahay 1989), *Cyamopsis tetragonoloba* (Sen and Daiya 1983), *Brassica juncea* "Varuna" (Damor and Vegada 1984); barley (Solanki *et al.* 1987), pearlmillet (Pandey *et al.* 1988; Kaushik and Gautam 1991), groundnut (Lourdraj *et al.* 1996), and *Capsicum annuum* (Mahalakshmi *et al.* 1999), where kaolin reduced A_{max} and E, resulting in improved plant water status and in a slower rate of soil water depletion as in barely (Ali and Prasad 1975), cotton (Singh *et al.* 1982), and tomato (Rao 1985). This delays the onset of severe water stress, with positive impact on yield. Many authors have already concluded that kaolin applications are more or only beneficial in water stressed conditions (De and Giri 1978b; Khan and Morey 1980; Singh *et al.* 1981; Uppal and Cheema 1981; Lombardini *et al.* 2004; Al-Moftah and Al-Humaid 2005).

However, in well irrigated plants, photosynthesis can be limited by heat stress, making the excessive incident radiation detrimental by increasing leaf temperature. Under such conditions, where high temperature, and not light, limits leaf photosynthesis and this is very low, kaolin applications can improve A_{max}, as it was shown in citrus at midday (A_{max} < 5 µmol CO_2 m^{-2} s^{-1}; Jifon and Syvertsen 2003) or apple (A_{max} < 8 µmol CO_2 m^{-2} s^{-1}; Glenn *et al.* 2001). At higher A_{max} kaolin reduces leaf photosynthesis as was observed in citrus in the morning ($A_{max} \approx 8$ µmol CO_2 m^{-2} s^{-1}; Jifon and Syvertsen 2003) and in apple (A_{max} > 15 µmol CO_2 m^{-2} s^{-1}; Grange *et al.* 2004; Wünsche *et al.* 2004). This hypothesis has been confirmed recently by Grange *et al.* (2004) who showed that kaolin applications on apple trees reduced A_{max} in all cases except in outer-canopy leaves exposed to high irradiance under high temperature and high vapour pressure difference. Similar results were found in walnut, where kaolin reduced leaf photosynthesis except in water stressed plants, later in the day, when photosynthesis was as low as 4 µmol CO_2 m^{-2} s^{-1} (Rosati *et al.* 2006). It may be concluded that in species, or under conditions where A_{max} is low and/or saturates at relatively low PAR levels, the kaolin-induced reduction in PAR absorption is less important, so that the beneficial mitigation of the heat stress may result in improved A_{max}. At higher A_{max}, as in non-stressed situations, the PAR reduction associated with kaolin is more likely to reduce leaf photosynthesis at any incident irradiance.

Gas exchange and PAR absorption

The above considerations explain the positive effect of kaolin applications in water and/or heat stressed plants with non-limiting light conditions. Under well irrigated conditions and mild temperature kaolin usually reduces leaf photosynthesis, but this does not appear to reduce canopy photosynthesis (Wünsche *et al.* 2004). Indeed, Glenn *et al.* (2003) found an increase in canopy photosynthesis, although only under high air temperature. Wünsche *et al.* (2004) speculated that this is due to improved light distribution within the canopy. Previous work had already suggested that kaolin increases light penetration (Doraiswamy and Rosenberg 1974; Lemeur and Rosenberg 1976). Rosati *et al.* (2007) showed that kaolin applications do indeed alter the light distribution within the canopy, increasing incident radiation on inner canopy leaves. This increase partly compensates for the reduction in PAR absorption of individual leaves with kaolin so that, for the whole canopy, PAR absorption is reduced much less than at the leaf level. In other words, the 20-40% loss of PAR absorption at the leaf level (Abou-Kaled *et al.* 1970; Moreshet *et al.* 1979; Wünsche *et al.* 2004; Rosati *et al.* 2006), due to increased PAR reflection, is in great part re-intercepted and eventually absorbed within the canopy. In walnut and almond, whole canopy *PAR* absorption was reduced by 7%, despite estimated reductions of 37% PAR absorption at the leaf level (Rosati *et al.* 2007). The small loss in PAR absorption by the canopy was more than compensated by an increase in photosynthetic radiation use efficiency (*PhRUE*), which was positively affected by the altered light distribution. In fact, skewing the light distribution towards inner-canopy leaves, results in improved canopy *PhRUE*, as was found in *Prunus* under water stress (Lampinen *et al.* 2004) or as commonly found with diffuse light, which penetrates the canopy better than direct radiation (Spitters 1986; Sinclair *et al.* 1992). Thus, even in well irrigated trees under mild temperatures, canopy photosynthesis may benefit from kaolin applications.

If this is the case, the question arises as to why the plants did not make white leaves in the first place. The answer might be that the benefits of kaolin applications on canopy photosynthesis and crop yield have been documented in environments with high incident irradiance, which were probably different from those where the species had evolved. With more cloudy weather (i.e. lower light and temperature) the documented benefits might not occur. For instance, in a light limited environment such as a greenhouse, kaolin application reduced the yield of beans (Tworkoski *et al.* 2002), and the plants showed typical symptoms of shade-grown plants such as altered shoot-to-root ratio and decreased stomatal density. Lower stomatal density was also found in other works (Subramanian and Sheriff 1992; Mahalakshmi *et al.* 1999), confirming the shade effect of kaolin. Additionally, in crops where the vegetation is less shaded in the inner canopy, as in small trees or in vegetable crops with discontinuous canopy cover, the positive effect of the altered distribution of light within the canopy might not occur.

CONCLUDING REMARKS

Under conditions of high incident radiation (i.e. sunny conditions), hot weather and water stress, kaolin applications appear often beneficial in terms of plant physiology and yield. However, whether or not these benefits alone make kaolin applications economically and environmentally viable is not clear. Stanhill *et al*. (1976), for instance, report that kaolin increased sorghum yield at a rate of two kg of grain per kg of kaolin, which does not appear very interesting economically. In non-stressed conditions, the benefits of kaolin applications in terms of plant photosynthesis and yield are probably very marginal when present at all.

It seems possible to conclude that, when used for pest and disease control or to prevent sunburn or else, kaolin application might additionally improve plant physiological activities, especially under hot weather, water stress and high incident irradiance. Under scarce incident irradiance, kaolin application might decrease plant productivity.

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REFERENCES

Abou Khaled A, Hagan RM, Davenport DC (1970) Effects of kaolinite as a reflective antitranspirant on leaf temperature, transpiration, photosynthesis, and water-use-efficiency. *Water Resources Research* **6**, 280-289

Ali M, Prasad R (1975) Soil-moisture studies in fallow-barley rotation under mulches, antitranspirant and type of seedbed. *Journal of the Indian Society of Soil Science* **23**, 163-171

Al-Moftah AE, Al-Humaid ARI (2005) Response of vegetative and reproductive parameters of water stressed tuberose plants to Vapor Fard and kaolin antitraspirants. *Arab Gulf Journal of Scientific Research* **23**, 7-14

Baradas MW, Blad BL, Rosenberg NJ (1976) Reflectant induced modification of soybean canopy radiation balance. IV. Leaf and canopy temperature. *Agronomy Journal* **68**, 843-848

Cottrell TE, Wood BW, Reilly CC (2002) Particle film affects black pecan aphid (Homoptera: Aphididae) on pecan. *Journal of Economic Entomology* **95**, 782-788

Creamer R, Carpenter J, Sanderson R, Sanogo S, El-Sebai OA (2005) Kaolin-based foliar reflectant affects physiology and incidence of beet curly top virus but not yield of chile pepper. *HortScience* **40**, 574-576

Damor UM, Vegada DA (1984) Effect of mulches and reflectant on the yield and quality of mustard *Brassica juncea* (L.) (Cozern and Coss) variety Varuna under limited irrigation. *Transactions of Indian Society of Desert Technology and University Centre of Desert Studies* **9**, 34-35

De R, Giri G (1978a) Effect of mulching and kaolin foliar spray on mung (*Vigna radiata*) – rapeseed (*Brassica campestris*) double cropping system under rainfed conditions. *Journal of Horticultural Science* **91**, 191-197

De R, Giri G (1978b) Effect of mulches and kaolin foliar spray on wheat yield on dry lands. *Indian Journal of Agricultural Sciences* **48**, 334-337

Dhiman SD, Sharma HC, Singh RP (1979) Role of agro-techniques in the production of rainfed wheat. *Indian Journal of Agronomy* **24**, 345-347

Doraiswamy, PC, Rosenberg NJ (1974) Reflectant induced modification of soybean canopy radiation. I. Preliminary tests with a kaolinite reflectant. *Agronomy Journal* **66**, 224-228

Glenn DM, Puterka GJ, Vanderzwet T, Byers RE, Feldhake C (1999) Hydrophobic particle films: a new paradigm for suppression of arthropod pests and plant diseases. *Journal of Economic Entomology* **92**, 759-771

Glenn DM, Puterka GJ, Drake SR, Unruh TR, Knight AL, Baherle P, Prado E, Baugher TA (2001) Particle film application influences apple leaf physiology, fruit yield, and fruit quality. *Journal of the American Society for Horticultural Science* **126**, 175-181

Glenn DM, Erez A, Puterka GJ, Gundrum P (2003) Particle films affect carbon assimilation and yield in 'Empire' apple. *Journal of the American Society for Horticultural Science* **128**, 356-362

Ingawale MV, Khanvilkar SA, Thorat ST, Patil BP (1988) Effects of irrigation, mulch and antitranspirant on the yield of greengram. *Journal of the Maharashtra Agricultural University* **13**, 160-161

Jambhale AS, Thorat ST (1988) Dry matter accumulation patterns in sunflower under varying levels of irrigation, mulch and antitranspirant. *Journal of the Indian Society of Coastal Agricultural Research* **6**, 127-131

Jifon JL, Syvertsen JP (2003) Kaolin particle film applications can increase photosynthesis and water use efficiency of 'Ruby Red' grapefruit leaves. *Journal of American Society for Horticultural Science* **128**, 107-112

Joshi AC, Patil JR, Umrani NK (1987) Use of mulch and anti-transpirant on groundnut under water stressed and non-stressed conditions. *Journal of the Maharashtra Agricultural University* **12**, 247-249

Kadbane VT, Mungse HB (1999) Effect of kaolin spray on transpiration, leaf temperature and RLWC behaviour of summer mung bean. *Journal of the Maharashtra Agricultural University* **23**, 274-276

Kaushik SK, Gautam RC (1991) Effect of dryland practices and plant population on the productivity and moisture use efficiency of pearl millet. *Indian Journal of Agronomy* **36**, 228-233

Khan GZ, Morey DK (1980) Influence of kaolin spray on transpiration and water use efficiency of ground nut (*Arachis hypogaea* L.) under different soil moisture regimes. *Journal of the Maharashtra Agricultural University* **5**, 131-134

Kumar K, Mavi HS, Khera KL, Singh L, Jhorar OP, Singh L (1992) Effect of shelter belt mulching and reflectant on field microclimate and yield of greengram (*Vigna radiata*) in south-west Punjab. *Annals of Agricultural Research* **13**, 335-339

Lampinen BD, Shackel KA, Southwick SM, Olson WH, de Jong TM (2004) Leaf and canopy level photosynthetic response of French prune (*Prunus domestica* L. "French") to stem water potential based deficit irrigation. *Journal of Horticultural Science and Biotechnology* **79**, 638-644

le Grange M, Wand SJE, Theron KL (2004) Effect of kaolin applications on apple fruit quality and gas exchange of apple leaves. *Acta Horticulturae* **636**, 545-550

Lemeur R, Rosenberg NJ (1976) Reflectant induced modification of soybean canopy radiation balance. 3. A comparison of the effectiveness of celite and kaolinite reflectants. *Agronomy Journal* **68**, 30-35

Lombardini L, Glenn DM, Harris MK (2004) Application of kaolin-based particle film on pecan trees: consequences on leaf gas exchange, stem water potential, nut quality, and insect populations. *HortScience* **39**, 857-858

Lourdraj AC, Geethalakshmi V, Devasenapathy P, Nagarajan P (1996) Drought management in rainfed groundnut. *Madras Agricultural Journal* **83(4)**, 265-266

Mahalakshmi BK, Rao DVS, Rao GR, Reddy PJ (1999) Management of drought with anti-transpirants in chilli (*Capsicum annuum* L.). *South Indian Horticulture* **47**, 86-88

Makus DJ (2000) Cotton performance as affected by particle film and Mycorrhizae treatments. *Proceedings of the Beltwide Cotton Conferences* **1**, 703-706

Moreshet S, Cohen Y, Fuchs ME (1979) Effect of increasing foliage reflectance on yield, growth, and physiological behavior of a dryland cotton crop. *Crop Science* **19**, 863-868

Pandey SK, Kaushik SK, Gautam RC (1988) Response of rainfed pearl millet (*Pennisetum glaucum*) to plant density and moisture conservation. *Indian Journal of Agricultural Sciences* **58**, 517-520

Pawar AB, Patil BB (1982) Effect of reflectant (kaoline) on yield, relative turgidity of leaf and albido of the canopy of summer mung (*Phaseolus aureus*) and cowpea (*Vigna catiang*). *Journal of the Maharashtra Agricultural University* **7**, 12-14

Puterka GJ, Glenn DM, Sekutowski DG, Unruh TR, Jones SK (2000) Progress toward liquid formulations of particle films for insect and disease control in pear. *Environmental Entomology* **29**, 329-339

Rao NKS (1985) The effects of antitranspirants on leaf water status, stomatal resistance and yield of tomato. *Journal of Horticultural Science* **60**, 89-92

Rao NKS (1986) The effects of antitranspirants on stomatal opening, and the proline and relative water contents in the tomato. *Journal of Horticultural Science* **61**, 369-372

Rao NKS, Bhatt RM (1990) Responses of onion to antitranspirants – plant water balance. *Plant Physiology and Biochemistry* **17**, 69-74

Rosati A, Metcalf SG, Buchner RP, Fulton AE, Lampinen BD (2006) Physiological effects of kaolin applications in well-irrigated and water-stressed walnut and almond trees. *Annals of Botany* **98**, 267-275

Rosati A, Metcalf SG, Buchner RP, Fulton AE, Lampinen BD (2007) Effects of kaolin application on light absorption and distribution, radiation use efficiency and photosynthesis of almond and walnut canopies. *Annals of Botany* **99**, 255-263

Russo VM, Díaz-Pérez JC (2005) Kaolin-based particle film has no effect on physiological measurements, disease incidence or yield in peppers. *HortScience* **40**, 98-101

Saour G (2005) Morphological assessment of olive seedlings treated with kaolin-based particle film and biostimulant. *Advances in Horticultural Science* **19**, 193-197

Saour G, Makee H (2003) Effects of kaolin particle film on olive fruit yield, oil content and quality. *Advances in Horticultural Science* **17**, 204-206

Schupp JR, Fallahi E, Chun IJ (2002) Effect of particle film on fruit sunburn, maturity and quality of 'Fuji' and 'Honeycrisp' apples. *HortTechnology* **12**, 87-90

Sen DN, Daiya KS (1983) Effect of antitranspirant on some kharif crops in arid agroecosystems. *Transactions of the Indian Society of Desert Technology and University Centre of Desert Studies* **8**, 138-144

Sinclair TR, Shirawa T, Hammer GL (1992) Variation in crop radiation-use efficiency with increased diffused radiation. *Crop Science* **32**, 1281-1284

Singh AK, Sinha AK, Nimgade NM (1982) Effect of evapotranspiration reducing techniques on soil water and temperature status in gram. *Transactions of the Indian Society of Desert Technology and University Centre of Desert Studies* **7**, 81-83

Singh RK, De R, Gangasaran, Turkhede BB (1981) Dryland wheat yield as affected by soil application of fertilizer nitrogen and farmyard manure and foliar application of kaolin and CCC. *Indian Journal of Agricultural Sciences* **51**, 167-172

Singh D, Sahay RK (1989) Effect of pix and kaolin on growth and yield of upland cotton (*Gossypium hirsutum*). *Indian Journal of Agricultural Sciences* **54**, 247-250

Showler AT (2002) Effects of kaolin-based particle film application on boll weevil (*Coleoptera: Curculionidae*) injury to cotton. *Journal of Economic Entomology* **95**, 754-762

Solanki NS, Singh RR, Chauhan RS (1987) Effect of nitrogen agro-chemicals and Azotobacter inoculation with and without FYM on yield and quality of rainfed barley. *Indian Journal of Agricultural Research* **21**, 83-87

Soundara Rajan MS, Ramkumar Reddy K, Sudhakar Rao R, Sankara Reddi GH (1981) Effect of antitranspirants and reflectants on pod yield of rainfed groundnut. *Agricultural Science Digest* **1**, 205-206

Spiers JD, Matta FB, Marshall DA (2003) Effects of kaolin clay particle film on southern highbush (*Vaccinium corymbosum* L.) blueberry plants. *Small Fruits Review* **2**, 29-36

Spitters CJT (1896) Separating the diffuse and direct component of global radiation and its implication for modeling canopy photosynthesis. Part II. Calculation of canopy photosynthesis. *Agricultural and Forest Meteorology* **38**, 231-242

Stanhill G, Moreshet S, Fuchs M (1976) Effect of increasing foliage and soil reflectivity on the yield and water use efficiency of grain sorghum. *Agronomy Journal* **68**, 329-332

Subramanian S, Sheriff NM (1992) The effect of anti-transpirants on the yield of cotton. *Madras Agricultural Journal* **79**, 427-430

Sugar D, Hilton RJ, van Buskirk PD (2005) Effects of kaolin particle film and rootstock on tree performance and fruit quality in "Doyenne du Comice" pear. *HortScience* **40**, 1726-1728

Thomas AL, Muller ME, Dodson BR, Ellersieck MR, Kaps M (2004) A kaolin-based particle film suppresses certain insect and fungal pests while reducing heat stress in apples. *Journal of the American Pomological Society* **58**, 42-51

Tworkoski, TJ, Glenn DM, Puterka GJ (2002) Response of bean to applications of hydrophobic mineral particles. *Canadian Journal of Plant Science* **82**, 217-219

Uppal HS, Cheema SS (1981) Effect of mulches and kaolin spray on soil temperature, growth, yield and water use of barley. *Indian Journal of Agricultural Sciences* **51**, 653-659

Unruh, TR, Knight AL, Upton J, Glenn DM, Puterka GJ (2000) Particle films for suppression of the codling moth (Lepidoptera: Tortricidae) in apple and pear orchards. *Journal of Economic Entomology* **93**, 737-743

Wand SJE, Theron KI, Ackerman J, Marais SJS (2006) Harvest and post-harvest apple fruit quality following applications of kaolin particle film in South African orchards. *Scientia Horticulturae* **107**, 271-276

Walters DR (2006) Disguising the leaf surface: the use of leaf coatings for plant disease control. *European Journal of Plant Pathology* **114**, 255-260

Wisniewski M, Glenn DM, Fuller MP (2002) Use of a hydrophobic particle film as a barrier to extrinsic ice nucleation in tomato plants. *Journal of the American Society for Horticultural Science* **127**, 358-364

Wünsche JN, Lombardini L, Greer DH (2004) Surround particle film applications – effects on whole canopy physiology of apple. *Acta Horticulturae* **636**, 565-571