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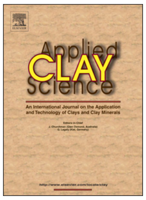

Review article

Particle films and their applications in horticultural crops

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ABSTRACT

Due to rising health concern, the idea of Good Agricultural Practices (GAPs) has emerged, especially for growing crops organically. In this context, several innovative technologies have been developed by agricultural scientists, such as the particle film technology (PFT). They are basically aqueous formulations made from chemically inert clay or mineral particles, which are specifically formulated for coating to reduce the damage caused by insects, diseases, solar injury, freeze injury and to improve fruit finish, color, carbon assimilation rate, yield and postharvest fruit quality. The development of the first such kaolin-based formulation, named Surround®, for commercial use was by Engelhard Corporation, Iselin, New Jersey (U.S.A.) in 1999. During the last two decades, a significant amount of research work has been conducted on the development of several such films (Surround® CF, Surround® WP, Raynox®, Cocoon™, Purshade™, Parasol®, Screen®, Snow®, Eclipse™, etc.) and their effects on various agricultural and horticultural crops. Considering the usefulness of these films, we attempted to compile the scattered information on the developed particle films, their modes of action and effects on various horticultural crops, in the form of a review. The review is particularly focused on history, modes of action, application and a variety of effects of particle films on horticultural crops.

1. Introduction

With the increasing awareness of consumers about harmful effects of the residues of pesticides, which are used for the production of horticultural commodities, there has been a rigorous search for some alternatives that could help in reducing the use of the toxic chemicals, which are not only a rising concern for the consumer health but also for environmental safety (Sharma et al., 2009). Perhaps, it is this concern that has forced the planners the recommendations of the use of Good Agricultural Practices (GAPs) throughout the world. As a result, several GAPs have been recommended for the production of horticultural commodities. One of the several innovations was the development of processed particle film technology (PFT). This includes the development of aqueous formulations from chemically inert mineral particles, which are specifically formulated for coating over the agricultural and horticultural produce as protective films (Stanley, 1998; Glenn and Puterka, 2004). These particle films exhibit several effects such as reduction in insect and plant pathogen damage, enhancement in the photosynthesis and yield of horticultural products, due to their several basic physical properties (Glenn and Puterka, 2005).

Most of the particle films are based on kaolin, a white, non-porous, non-swelling, low-abrasive, fine grained, plate-shaped, alumino-silicate mineral [$Al_4Si_4O_{10}(OH)_8$], which disperse easily in water and are chemically inert over a wide range of pH (Glenn and Puterka, 2005). This is a secondary mineral, derived from the primary minerals which occur naturally as inorganic substances in the soil and sediments. Mined, crude kaolin contains traces of Fe_2O_3 (ferrous oxide) and TiO_2 (titanium oxide) that are removed during processing to increase its brightness. Water-processed kaolin is >99% pure and has >85% brightness (Glenn and Puterka, 2005). However, crystalline silica, SiO_2, a respirable human carcinogen, must be removed to ensure human safety (Harben, 1995). With the technical advancement in kaolin processing, it is now possible to produce kaolin particles with specific shapes, sizes, and with light reflective properties (Glenn et al., 2002).

Traditionally, kaolin was used in ceramics, medicine, bricks, coated paper, as a food additive, in toothpaste, as a light diffusing material in white incandescent light bulbs, and in cosmetics and as a filler in many other applications (Glenn et al., 2002). Kaolin has even been used for spiritual and healing purposes. The largest and most common use of kaolin is in the paper industry, where it has been the main ingredient in creating 'glossiness' in the paper. Potential uses of kaolin particles have been ignored by the agricultural and horticultural industry except for its use as carrier for wettable powder formulations of some pesticides. With the increase in interest and knowledge, several

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advances have been made by the scientists in kaolin processing, formulation and plant surface deposition properties, which have opened new avenues for its use as an integral part of organically grown horticultural crops.

2. History of mineral particle film use

In nature, many animals commonly take 'dust baths' to save themselves from insect parasites and attacks from biting insects. Soil dusts have also been used as insect repellents by primitive people, mammals and birds regularly to avoid insect bites (Ebling, 1971). In ancient times, elemental sulfur or sulfur compounds along with bitumen were used to be heated to generate sulfur fumes to repel insects from vines and trees (Smith and Secoy, 1975). In the very early days, diatomaceous earth (diatomite) was used to protect plants from pests in China (Allen, 1972). Since then, there is a long history on the use of various mineral-based preparations, and some of these are still used for special purposes in agricultural or horticultural pest control. Arsenic and arsenic salts were used in China around 900 C.E., and were being incorporated into ant baits in Europe during 1699 (Casida and Quistad, 1998).

During the first century AD, powdered limestone (calcium carbonate) was added to grains for deterring storage insect-pests. A mixture of hydrated lime and sulfur was one of the primary insecticides and fungicides of early agri-horti production systems (Secoy and Smith, 1983). Hydrated lime or sulfur was applied either alone or in combination to protect several agricultural and horticultural crops from insect damage. Furthermore, chemically reactive hydrated lime and sulfur were being applied along with tobacco, wood ash, linseed oil, soap and cow dung as paints or washes to fruit trees and grapevines to protect them from insect and disease damage. Slaked lime [$Ca(OH)_2$] and burnt lime [CaO] were used against household, stored grain and crop insect pests during the late 1500s to the 1800s. Sulfur in combination with limestone were burnt as a fumigant for trees, while lime-sulfur preparations became popular in the later part of the 18th century, which replaced the application of individual minerals. Thus, in the older time, lime sulfur, slaked lime and sulfur were the main materials for insect and disease control as these were easily prepared.

In the 1920s, use of dust applications over liquid sprays was preferred because of the ease and speed of dusting operations, good plant coverage, economy in labor, and comparable insect control with liquid sprays (Giddings, 1921; Headly, 1921). The increased interest in the use of dusts to deliver insecticides was proposed from research that indicated 'self cleaning' response of chemically active particles of sodium fluoride and borax (Shafer, 1915; Mote et al., 1926), which was primarily due irritation leading to death by the ingested particles. In the 1930s, it was established that certain 'inert dusts' themselves had toxic activity against insects when ingested during the process of self cleaning (Boyce, 1932; Richardson and Glover, 1932).

Insecticidal dusts were used as a primary means of delivering insecticides in the 1940s. Watkins and Norton (1947) found that abrasive dusts like alumina-aluminum oxide (Al_2O_3) or silica oxide (SiO_2) were the best carriers of DDT. Between the 1950s and 1960s, non-abrasive sorptive dusts like montmorillonite and attapulgite were found to remove the thin lipid layer covering the epicuticle of dry wood termites. The ability of finely divided particles to adsorb and remove the cuticular waxes of insects was proved by Ebling and Wagner (1959). Interest in the control of insects with inert dusts has transitioned from minerals to synthetic compounds like silica aerogels and fumed silicas by 1970.

The research on mineral particles after 1970 was limited to pesticide formulations in which mineral particles were used as carriers for synthetic pesticides (Kirkpatrick and Gillenwater, 1981; Margulies et al., 1992) or microbial agents (Studdert et al., 1990; Tapp and Stotzky, 1995) and in the use of minerals as white-wash sprays for preventing plant viral diseases that were spread by aphid vectors (Adlerz and Everett, 1968; Bar-Joseph and Frenkel, 1983) and thrips (Smith et al., 1972). Mineral based white-washes have been examined for the prevention of insect vectored transmission of plant viral diseases. White reflective surfaces repel certain aphids by affecting their host-finding and settling responses (Kennedy et al., 1961; Kring, 1962).

White-washes come in various forms and are generally composed of kaolinite, bentonite, and attapulgite with the addition of spreading and sticking agents that are designed to white-wash the plant stem, foliage or soil surrounding the plant (Nawrocka et al., 1975; Bar-Joseph and Frenkel, 1983; Marco, 1986, 1993). This approach was successful but was limited to repel aphids and leafhoppers, which act as vector for the spread of several viral diseases of horticultural crops. In the 1980s, kaolin based sprayable mulch was developed and demonstrated to be effective against *Aphis spiraecola* Patch, in citrus (Bar-Joseph and Frenkel, 1983). White-wash spray for insect control couldn't become popular and was of little scientific interest until development of several particle films such as 'Surround', 'Cocoon', 'Parasol', 'Purshade', 'Screen', and 'Eclipse', which have led to new possibilities for its use in agricultural related activities.

3. Commercialization of particle film technology

The wild idea for research on particle film technology was perceived from the fact that mineral particles have a significant influence on insect behavior which was not previously recognized (Glenn et al., 1999; Puterka et al., 2000a). As a result, research on particle film was initiated during 1994 with the attempt to control fruit diseases with hydrophobic kaolin films. Hydrophobic kaolin particle film (M96-018) was co-developed by the United States Department of Agriculture (USDA) and Engelhard Corporation, Iselin, New Jersey, the world leader in surface and materials science, through several years of development.

The film was quite effective against insects and mites on apple and pear but due to problems in its mixing with water and lack of adhesiveness to plant, made it impractical (Glenn, 1999). A year later, a methanol (MEOH)–water system was developed in which hydrophobic film could be pre-slurried and easily sprayed on trees but it was quite expensive and difficult to handle and transport it. Moreover, methanol was listed as hazardous material in the U.S. (Puterka et al., 2000a). Considering these problems, the scientists at the Engelhard Corporation, Iselin, New Jersey, developed hydrophilic kaolin based film, M97-009 which required a non-ionic spreader-sticker, M03. The material in this film was similar to M96-018 but without silicon coating having a particle size of less than 1.0 μm in diameter. This formulation was quite effective in controlling insects and diseases under lab as well as field conditions (Puterka et al., 2000a,b).

Advantages of using the hydrophilic films were: i) ease of mixing, ii) less expensive, iii) good compatibility with other spray materials, and iv) easy spreadability over tree canopy. These formulations (M97-009 + M03) were named as Surround® Crop Protectant and made commercially available in 1999 (Corporation, Iselin, New Jersey). Although this formulation was quite effective against insect-pests but handling and shipping of two package system (particles + spreader-sticker) was quite problematic. Hence, research was focussed for the development of a single package system. As a result, Surround® Crop Protectant was replaced by Surround® WP, which contained kaolin particle with sticker and spreader agents (Glenn and Puterka, 2005). In 2002, Surround® CF was developed and made commercially available which is similar to Surround® WP but has different spreader-sticker which speeds up the mixing at low temperature (4–10 °C).

The developed particle-based formulations offer several important qualities, such as: reflectance of the sun's heat; easy mixability in water; good coverage capacity; and good adherence to the plant canopy and fruit. Now, several particle film formulations such as Surround® (95% Calcined kaolin), Surround® CF, Surround® WP, RAYNOX®, RAYNOX AIR, RAYNOX ORGANIC, Cocoon™(100% hydrous kaolin), Parasol®, Anti-stress 500®, Purshade® (62.5% limestone), Screen®, Snow®, Eclipse™(Ca + B), Fruit Shield (Black particles) and Savona®

SL (Potassium salt of fatty acids), are available in the global market for their commercial use in horticultural crops for several desirable effects (Warner, 2006; Ergun, 2012; Prager et al., 2013).

4. Characteristics of an ideal particle film

For a particle film to be used over any horticultural crop, it should possess the following characteristics:

- should be a chemically inert mineral particle,
- particle diameter should be <2 μm,
- should have the ability to get formulated to spread and create an uniform film over the produce,
- should form a porous film which should not interfere with the gas exchange from the leaf without blocking stomata,
- should transmit photosynthetically active radiation (PAR) but exclude ultraviolet (UV) and infrared (IR) radiation to some extent,
- should have the ability to alter insect or pathogen behavior on the commodity to be treated and
- should have the ability to get removable easily from the harvested produce.

Most of these characteristics are similar to natural defenses found in plants such as presence of increased cuticle thickness and pubescence to reduce water and heat stress (Levitt, 1980) and to interfere with disease and insect damage (Barthlott and Neinhuis, 1997; Neinhuis and Barthlott, 1997).

5. Application of particle films

5.1. Rate and method of application

In general, the rate of application of the particle film is dependent on the amount of plant surface to be covered and active ingredients of the film. In general, Surround WP is recommended to be used @ 2.5 to 5 kg/ha, depending on the crop to be sprayed and desirable effects to be achieved (Glenn and Puterka, 2005). Sufficient spray volume should be used in order to obtain good coverage, which usually means a thorough near-drip application, not to run-off (Glenn and Puterka, 2004, 2005). In order to cover all the plant parts which are to be protected, two or more applications/sprays are always required. For optimal performance against pests like pear psylla, particle film must coat both sides of the leaves. Application to tree crops can be done using commercial air-blast or high pressure sprayers that provide enough air turbulence to coat both sides of the leaf, bark and fruit. After application, plant surfaces will usually turn a hazy white after drying while additional applications will turn the plant surfaces deeper white. When dry foliage has lost its white appearance, re-application should be done immediately (Glenn and Puterka, 2004, 2005).

For a 20-feet tree, it is best to use 935–1871 l of water per ha. Large trees such as walnut or pecan require up to 2806 l of water per ha. Depending on the crop, the particle films can be applied at rates ranging between 12 and 50 kg per ha. When mixing in a tank, the particle films should be added to the tank first and a pre-mix tank is suggested for sprayers without mechanical agitation. Aerial application of particle films in not recommended for effective insect suppression, because of inadequate coverage on all sides of plant surfaces, such as on the undersides of leaves, which is difficult to achieve via aerial application (Glenn and Puterka, 2004). The Surround WP label specifies that it should be applied in a minimum of 2339 l per ha spray volume. However, due to sprayer configuration and speed of application considerations, most Arizona citrus producers are reluctant to exceed 935.4 l per ha spray volumes.

5.2. Time of application

Particle films should be applied before the occurrence of pests or high temperature and must be reapplied every two weeks to protect new growth or after a heavy rain. Correct application timing is essential to optimize protection. For optimum effectiveness, these particle films should be used in a preventive program and sprayed before the insect appears, so as to establish good coverage by the film before the infestation (Glenn and Puterka, 2004, 2005).

5.2.1. Water based particle emulsions

Initial application for such films (e.g., Surround) should start prior to infestation and later the interval of application varies with the type of crop and kind of pest (Table 1).

5.2.2. Wax-based emulsions

Some wax based emulsions such as Raynox® have also been developed. Apples are most vulnerable to sunburn when air temperature is 30 °C with low humidity. Applications need to start before sunburn occurs and effective sunburn reduction occurs using a 4–5 spray program (Schrader et al., 2003; Schrader, 2011) as under:

- The first spray should be applied 7 weeks after full bloom. This usually occurs about mid–late November but make sure that it should be applied before the first heat event around this time.
- A second spray should be applied 7–10 days later.
- The third spray should be given 3 weeks later.
- The fourth spray should be given 4 weeks later.
- The fifth spray (if needed) should be made 4 weeks later, and
- Any subsequent applications that may be needed should be made at monthly intervals.

6. Modes of action of particle films

Particle films exhibit several desirable effects on different fruits and can be used for controlling or reducing insect-pests, diseases, solar and freeze injury and can improve the fruit finish. Such effects are attributed to different modes of actions of these films.

Table 1
Time and amount of particle films application on horticultural crops.

Crop	Frequency of particle film application	Targeted pest
Apple, pear	Tree applications @ 7–10 day interval	Apple sawfly, pear psylla, gypsy moth
Stone fruits	3–4 applications @ 5–7 day interval	Japanese beetle/Rose chaffer
Berries	2–3 sprays @ 7–14 day interval	Blackberry-maggots, psyllid, beetle, grasshopper
Citrus	Two pre-bloom sprays at 5–7 day interval and two post-bloom sprays at 7–14 day interval	Thrips, leaf hoppers, psyllids
Grape	1–3 applications @ 7–14 day interval	Thrips, leaf hoppers
Pecan	2 sprays @ 4–14 days	Aphids
Legume vegetables	2 sprays @ 7–14 day interval	Leaf beetles, grass hoppers
Root & tuber vegetables	2 sprays @ 7–14 day interval	Flea beetle, leaf hopper
Fruit vegetables	2 sprays @ 7–14 day interval	Beetles, grasshoppers, thrips, flea beetles
Bulb vegetables	2 sprays @ 5–7 day interval	Thrips
Leafy vegetables	2 sprays @ 3–5 day interval	Grass hopper, flea beetles
Asparagus	2 sprays @ 7–10 day interval	Beetles, grass hoppers

6.1. Fruit finish

Consumers prefer fruits having good attractive color and finish. Several fruits become unattractive to consumers due to poor finish which usually occurs due to rough handling during grading, packing, transportation and subsequent marketing. Particle films improve fruit finish in some fruits by reducing russeting (Glenn et al., 2001b; Prive et al., 2007a). Although the mechanism involved is not fully understood but it appears that interference with microbial activity on the fruit surface is associated with epiphytic microbial population which is responsible for russeting in some fruits (Matteson-Heidenreich et al., 1997).

6.2. Insect pest damage

When particle films are used on fruit plants, the plant tissues coated with films are obviously altered visually and tactilely towards pests (Glenn and Puterka, 2005). Thus, one of the first modes of action of particle films is the host camouflaging, which makes plants unrecognizable to enemies. By camouflaging, particle films reduce pest oviposition and the overall pest population in the microclimate of the plant foliage. Particle films also suppresses insect pests by repellency, impeding egg laying, reducing feeding, impeding grasping, restricting their movement, behavior alteration, paralysis induction and by causing mortality (Glenn et al., 1999; Puterka et al., 2000b).

The mechanisms underlying how particle films affect the biology and behavior of insect pests have been extensively explored by several authors (Cadogan and Scharbach, 2005; Puterka et al., 2005; Lemoyne et al., 2008), describing a variety of effects i.e., direct toxicity and interference with insects ability to settle, move or oviposit (Hall et al., 2007). Porcel et al. (2011) studied the biological and behavioral effects of a kaolin particle film on larvae and adults of *Chrysoperla carnea* Stephens and found that a higher number of *C. carnea* adults were found associated with kaolin treated olive trees which indicate that, disruption of movement capacity and dislodgment from the plant surface may be the main negative actions of particle films on *C. carnea* larvae while adults showed a positive trend in oviposition and abundance towards kaolin treated surfaces.

6.3. Disease control

Many fungal and bacterial plant pathogens require a liquid film of water for propagule (Spores/Conidia) germination and direct contact with the leaf surface. The particle films envelop the leaf which prevents direct contact of spores or water with the leaf surface and thereby suppresses the infection. Such films also inhibit the adhesion of fungal spores to the leaf surface which reduces the chances of infection and lesion development (Walters, 2006). For example, a combination of aluminum, silica, and titanium dioxide was effective in controlling downy and powdery mildew of grapes (Mendgen et al., 1992) and scab in apple (Prive et al., 2007a) through mechanisms that may include:

i) direct action on the hyphae,
ii) interference with recognition of the plant surface, and
iii) stimulation of the plant's physiological defenses. Antitranspirant films reduced the incidence of powdery mildew and other general cucurbit diseases (Ziv and Zitter, 1992), and powdery mildew of Zinnia (Kamp, 1985). Similarly, antitranspirant films form an artificial barrier on the plant surface that interferes with the infection process.

6.4. Solar injury

Solar injury to fruits occurs with high temperature and solar radiation. When particle films are applied to fruits, they leave sufficient amount of residue on the fruit surface. This residue reduces the fruit temperature and thereby the solar injury (Glenn and Puterka, 2004, 2005).

6.5. UV damage

Ultraviolet radiation is a natural component of the broad EMS (Electro Magnetic Spectrum) and categorized under three bandwidths: UVa (315–400 nm); UVb (280–315 nm); and UVc (195–280 nm). Ultraviolet radiation damages the plants by forming DNA dimers, inhibition of photosystem II and Rubisco activity. The particle films such as Surround ® containing kaolin are reflective to UV radiation and their degree of reflection depends on the particle formulation and their size distribution. The highly processed kaolin formulation has greater UV reflection than the unprocessed kaolin or calcium carbonate (Glenn et al., 2002). Thus, the main principle behind reduction in UV damage by particle films is the reflection of light by such films.

6.6. Freeze damage

It has been established that particle films protect the fruit plants from freeze damage. The damage to the plants and or fruits of subtropical and tropical regions is quite high than species of temperate region. When water freezes on the plant surface, and ice nucleation starts within the plant by the physical growth of ice crystals into the interior plant parts through stomata, lenticels, cuticular cracks, wounds, broken epidermal hairs, and/any other lesions, the activity of the extrinsic nucleators and subsequent ice crystal formation into the plant parts can be blocked and allow the plant to super cool and get freeze protection.

The particle films applied over the plant surface acts as a physical barrier separating the water from the plant surface. It has been established that hydrophobic films (M96-018) can prevent freeze injury by separating the dew or frost from the plant surface physically (Glenn et al., 2001a). Similar effect of hydrophobic particle film on ice nucleation and freeze damage prevention was reported in whole tomato plants (Wisniewski et al., 2002; Fuller et al., 2003).

7. Impact of particle films on horticultural crops

7.1. Fruit color

The external fruit color plays a vital role in consumer preference. Fruit peel color is one of the most important factors in consumer fruit quality perception (Andris and Crisoto, 1996). The particle film technology has demonstrated that a reduction in infrared and ultraviolet light as well as the redistribution of photosynthetically active radiation results in improved red color development in apple. Some growers reported that particle films improved apple fruit color — particularly in hard-to-color apple varieties and on the blind side of the fruit. This improvement in coloration results from the increased scattering of light within the canopy caused by reflection from the particle films deposited on the leaves.

Glenn et al. (2005) observed consistent improvement in red color of apple cv. ‘Empire’ with season-long applications of particle films. They also observed that cv. ‘Gala’ had greater fruit weight and red color with particle film application in West Virginia but not in Washington. Red blush on apples (anthocyanins) has sometimes been reduced by Surround WP applications (Schupp et al., 2002; Gindaba and Wand, 2005). The increased reflectance by Surround WP might possibly reduces photo-protective compounds responsible for color development (Glenn et al., 2002; Wunsche et al., 2004). Kaolin treatments increased trans-lycopene content of tomato fruits on average by 14%, while there was no influence on other qualitative parameters observed (Pace et al., 2007). The kaolin based reflective ground covers under black hailnet has improved the proportion of well-colored class-I apple fruit (Meinhold et al., 2011).

7.2. Fruit finish

In addition to color, external appearance of fruit also has great bearing on its market value. Usually, it is one of the most difficult tasks to maintain the external fruit look in the orchard because fruits have a tendency to roughen up and russet as the season progresses. Several factors associated with poor fruit look such as mildew infections, frost, yeast infections, high heat and UV, and copper compounds applied at the wrong time, are mainly associated with it. In addition, excessive wetting, inappropriate combinations or mixes of chemicals also contribute to poor look of fruits (Glenn et al., 2001b; Sugar et al., 2005; Gardner, 2007). Kaolin treatment reduced the extent of russetting on the 'Comice' pear fruit surface without adverse effects on tree growth and performance (Sugar et al., 2005). Gardner (2007) treated apple trees with (Promalin [BA + GA] + Surround) which produced a lemon yellow colored fruits with a silky smooth finish and inconspicuous lenticels. In contrast, the untreated trees produced fruits with a rougher finish that was characterized by a much higher % of lenticel spotting having greenish yellow color.

7.3. Harmful insects

Among different pest management strategies used in organic agriculture, the use of pest control substances of biological and mineral origin has the advantage of directly reducing the abundance of pests in cases where preventive measures have miserably failed (Zehnder et al., 2007). Kaolin based formulations provide an effective control of a variety of arthropod pests in different crop systems and are therefore widely used for pest management, mainly in organic agriculture. Their efficacy often outperforms other insecticidal agents used in organic farming, especially in dry regions where there is less frequent precipitation and a lower risk of wash-off (Mazor and Erez, 2004; Saour and Makee, 2004; Karagounis et al., 2006).

Particle film technology, while still in its infancy, represents a broadly-based insect control system whose impact could be similar to the development of the first synthetic insecticides but without the adverse effect on environment and food-chain characteristics. It has been demonstrated that this technology effectively provides a safe replacement for some of the organophosphate and carbamate insecticides used in a wide range of crops, including apple, pear, grape, blackberry, tomato, peach, and nectarine (Unruh et al., 2000; Mazor and Erez, 2004). Due to its low toxicity and safe handling properties, the US Environmental Protection Agency (EPA) registration process 'fast-tracked' this material to make it available for large number of growers as soon as its creation. The formulations contained only compounds, which are present in the Food and Drug Administration's 'Generally Recognized As Safe' list.

Although, kaolin particle technology is relatively new, yet it provides promising option for the reduction of insect pest damage in certain horticultural crops (Table 2). In this technology, the plants are dusted or sprayed with non-abrasive, chemically inert, alumino silicate mineral particles creating a film that coats the plant and act as a protective barrier against insect pests (Glenn et al., 1999). The use of kaolin films are effective against a wide range of insect pests such as psyllids, leaf miner, codling moth, Mediterranean fruit fly, aphids, pear psylla, medfly, black scale, thrips and several other pests, which infest several fruits and vegetables (Table 2). Particle film technology also have the advantage of being allowed in organic agriculture, standing out, alongside with mass-trapping (Porcel et al., 2009) and natural derived pesticides (Iannotta et al., 2007) as one of the few options available for organic olive growing to control *Bactrocera oleae* damage.

7.4. Beneficial insects

This novel pest control knowledge is useful in joint strategies where alternative pest control methods should not interfere with biological control. In this sense, recent literature has generally focused on field assessment of kaolin effects based on the presence or absence of beneficial insects and/or arthropods on kaolin treated crops (Karagounis et al., 2006; Marko et al., 2007; Sackett et al., 2007; Pascual et al., 2010). Till date, concrete effects caused by kaolin films to beneficial insects have received little attention, and in the case of predators, little information on possible behavioral and biological disruptions is available.

Research on the effects of particle films on beneficial insects has demonstrated that lady beetles operate well against aphids on plant surfaces treated with kaolin particle films. Although, some reduction in parasitism has been noted as the role of predators and parasites should be minimal due to the low number of prey available. On the other hand, the particle film does not generally affect honeybees and other pollinators as long as it is not applied while honeybees forage. Similarly, it has been reported that kaolin applications bring about a reduction in the levels of parasitism of leaf miner moths and apple sawfly (Knight et al., 2001; Marko et al., 2008) and disruption of predation by arthropods such as spiders, earwigs (*Forficula auricularia* L.) and red velvet mites [*Allothrombium fuliginosum* (Hermann)] (Knight et al., 2001; Sackett et al., 2007; Marko et al., 2008). Kaolin particle films can cause a reduction in the activity of natural enemies and may therefore, to some extent, compensate or even overcompensate for the negative effects of kaolin treatments on their host/prey species (Knight et al., 2001; Marko et al., 2008).

In olive orchards, the green lacewing is considered the major predator of the olive moth (*Prays oleae*) and it helps in the reduction of economic impact of this pest (Tauber et al., 2000; Medina et al., 2003; Mandour, 2009). It also preys upon other lesser known harmful insects such as the black scale and the olive psylla (Campos, 2001). Studies undertaken in different crops have detected a decreased abundance and alteration of the assemblages of polyphagous predators associated with kaolin treatments (Marko et al., 2007; Sackett et al., 2007; Pascual et al., 2010; Porcel et al., 2011). Similarly, Marko et al. (2010) found that applications of hydrophobic particle films significantly reduced the incidence of beetles and maintained the abundance spiders in apple orchards in the Netherlands.

7.5. Diseases

After years of experiments, Glenn et al. (1999) proposed a new concept of disease control using hydrophobic kaolin particle films. In this method, a hydrophobic layer of particles keep water physically separated from the plant surface which helps in suppressing several diseases such as powdery mildew, sooty blotch, fly speck, and fire blight (Bowen et al., 1992; Mendgen et al., 1992; Menzies et al., 1992). The particulate material did not interfere with the action of conventional bactericides, fungicides or pH modifying agents. Puterka et al. (2000b) demonstrated that *Fabraea* leaf spot (*Fabraea maculata*) of pear was suppressed by both hydrophobic and hydrophilic kaolin particles, presumably through physical interference in the infection process and a lack of adherence of inoculum to the plant surface. In addition, there was an increase in pear fruit yield that was thought to result from the reflective nature of the particles that reduced plant temperature (Glenn et al., 1999, 2001b).

Potassium silica application was effective in reducing powdery mildew in apple (Bowen et al., 1992; Menzies et al., 1992). White wash was useful in suppressing the transmission of citrus stubborn disease (Gumpf et al., 1981) and papaya decline (Franck and Bar-Joseph, 1992). A combination of aluminum, silica, and titanium dioxide was effective in controlling downy and powdery mildew of grapes (Mendgen et al., 1992) through mechanisms that may include: 1) direct action on the hyphae, 2) interference with recognition of the plant surface, and 3) stimulation of the plant's physiological defenses. However, kaolin particle films failed to control peach scab or rusty spot, but hydrophobic kaolin effectively controlled peach brown rot while hydrophilic kaolin failed to provide any control (Lalancette et al., 2005). Creamer et al.

Table 2
Influence of particle films on insect pests of different fruits and vegetables.

Crop	Cultivar	Targeted insect-pest	Particle film applied	Mode of action	Remarks	Reference (s)
A. Fruit crops						
Apple	Smoothee	*Aphis spiraecola*, *Tetranychus utricae*, *Empoasca fabae*	M96-018 dust	Mortality	Also reduced incidence of apple scab	Glenn et al. (1999)
	Fuji, Gala, Red Delicious and Golden Delicious.	Codling moth (*Cydia pomonella*)	M96-018 + MeOH, Surround + M03	Repellence, Reduced oviposition	Neonate larval walking speed, fruit discovery rate, fruit infestation and fruit penetration rate were lowered.	Lapointe (2000)
	Gala	Medfly (*Ceratitis capitata*)	Surround ® WP (6%)	Female repellence and reduced oviposition	Application of kaolin particle film resulted in practically clean fruits than the control.	Mazor and Erez (2004)
	Golden Delicious	Apple maggot (*Rhagoletis pomonella*)	Surround ®	Interference with visual cues	Reduced damage by maggot infestation.	Villanueva and Walgenbach (2007)
	Delicious	Oblique banded leafroller, (*Choristoneura rosaceana*)	Kaolin + synthetic insecticides	Kaolin alone doesn't have any effect on leafroller mortality	Kaolin particles increased the toxicity of the azinophosmethyl and indoxacarb	Smirle et al. (2007)
	James Grieve, Golden Delicious, Cox's Orange Pippin	Most pests	Kaolin-M96-018	Reduced fruit infestation and damage	Suppressed many pests but no effect on rosy leaf curling aphid, common earwig, apple saw fly and aphid	Marko et al. (2008)
	Delicious	Codling moth (*Cydia pomonella*)	Surround®, Cocoon and Eclipse	Repellency	No significant protection for granulovirus (CpGV) from UV radiation	Arthurs et al. (2008)
	Sun Fuji, Crimson Gala	Apple maggot (*Rhagoletis pomonella*)	Surround ® WP	Reduced attractiveness of fruit based visual-cues	It acted as a tactile deterrent, reduced residence time and had toxic effect on adults	Leskey et al. (2010)
	Glockenapfel, Topaz	Rose apple aphid (*Dysaphis plantaginea*)	Surround ® WP	Repellency	Significantly reduced females in autumn season	Burgel et al. (2005)
	Golden Delicious, Fuji	Oblique banded Leafroller (*Choristoneura rosaceana*)	M96-018 + MeOH	Reduced female longevity and oviposition	–	Knight et al. (2000)
Pear	Bartlett	*Cacopsylla pyricola*	M96-018 dust	Repellence and reduced oviposition	Reduced heat stress by reflection of sunlight	Glenn et al. (1999)
	Bartlett	Codling moth (*Cydia pomonella*)	M96-018 + MeOH, Surround + M03	Repellence, Reduced feeding damage and oviposition	Neonate larval walking speed, fruit discovery rate, fruit infestation and fruit penetration rate were lowered	Unruh et al. (2000)
	Seckel	*Cacopsylla pyricola*, *Epitrimerus pyri*, *Conotrachelus nenuphar*, *Cydia pomonella*	M96-018 dust and MeOH, Surround + M03	Repellecne, reduced incidence, damage and ovipositon	Suppression and reduced feeding.	Puterka et al. (2000b)
	Louise Bonne	European pear sucker (*Cacopsylla pyri*)	Surround ® WP	Reduced nymph population	The population of pear sucker was kept under damaging level.	Daniel et al. (2005)
	Abbe Fetel	Pear psylla (*Cacopsylla pyri*)	Surround ® WP. Mineral oil	Hindering the anchorage on leaf surface and inhibiting host plant acceptance	Neither egg masses nor nymphs were observed on treated plants.	Pasqualini et al. (2002)
	Bartlett	Pear psylla (*Cacopsylla pyri*)	Surround and Surround WP	Deterred adult settling and oviposition	Adult mortality was in the range of 22–62% while nymph mortality was 58.9–82%.	Puterka et al. (2005)
	Koshia	Pear psylla (*Cacopsylla pyri*)	Surround® (Kaolin) Envidor® (Spirodiclofen Acaricide)	Effectively suppressed the nymph densities.	Increased fruit load in treated plants	Saour et al. (2010).

(continued on next page)

Table 2 (*continued*)

Crop	Cultivar	Targeted insect-pest	Particle film applied	Mode of action	Remarks	Reference (s)
			Vitazyme® (Org. biostimulant) Messenger® (Harpin protein)			
Lemon	Limoneira 8A Lisbon	Thrips (*Scirtothrips citri*)	M96-015 + MeOH	Reduced fruit and flush infestation	Controlled thrips and increased fruit size.	David and Glenn (2001)
	–	Broad nosed weevil (*Diaprepes abbreviates*)	Kaolin particles (clay mineral)	Feeding deterrent, reduced oviposition	Prevented sticking of eggs to leaf surface. Feeding by adult weevil was reduced by 68–84%.	Lapointe (2001)
	–	*Diaphorina citri*	Surround ® WP	Repellence	–	McKenzie et al. (2002)
Citrus macrophylla	–	Diaprepes root weevil (*Diaprepes abbreviates*)	Surround® WP	Deterrence on feeding and oviposition, reduced fecundivity	Particle film deterred the feeding and oviposition in proportion to its concentration.	Lapointe (2005)
Sweet orange	Midsweet	Citrus root weevil (*Diaprepes abbreviates*)	Surround® WP	Reduced oviposition	Reduced the number of egg masses over treated trees but the larval population was greater than the control	Lapointe et al. (2006)
	Hamlin	Psyllid (*Diaphorina citri*)	Surround ® WP	Interfered with the ability of the adults to grasp and walk on treated leaves.	No. of eggs and nymphs per flush shoot were reduced by 85 and 78% respectively.	Hall et al. (2007)
Mandarin	Satsuma	Medfly (*Ceratitis capitata*)	Surround ® WP	Repellence	Reduced punctures and landings over the treated fruit. Reduced postharvest decay.	Aquino et al. (2011)
Nectarine	Flamekist	Medfly (*Ceratitis capitata*)	Surround ® WP (6%)	Repellence and Camouflaging	Application of kaolin particle film resulted in practically clean fruits than the control.	Mazor and Erez (2004)
	Sunsnow	Medfly (*Ceratitis capitata*)	Surround ® WP (6%)	Deterrence for oviposition	Female flies avoided landing on treated leaves.	Mazor and Erez (2004)
	Fairline and Venus	Medfly (*Ceratitis capitata*)	Surround ® WP	Repellence	Reduced punctures and landings over the treated fruit. Reduced postharvest decay.	Aquino et al. (2011)
Pecan nut	Curtis	Black Pecan Aphid (*Melanocallis caryaefoliae*)	Surround + M03	Restricted mobility	Adult mortality was high and there was a decrease in the production of nymphs	Cottrell et al. (2002)
	Pawnee	Pecanut case borer (*Acrobasis nuxvorella*)	Surround ® WP (5%)	–	Damage was more in particle film treated (24.2%) compared to conventional insecticide treated (9.3%) nuts.	Lombardini et al. (2005)
Peach	–	Oriental fruit moth (*Grapholita molesta*), Plum curculio (*Conotrachelus nenuphar*), Japanese beetle (*Popillia japonica*)	–	–	Effectively controlled their populations	Lalancette et al. (2005)
	'Fairtime' and 'Regina di Londa'	Medfly (*Ceratitis capitata*)	Surround ® WP	Repellence	Reduced punctures and landings over the treated fruit. Reduced postharvest decay.	Aquino et al. (2011)
Sweet Cherry	Royal Anne, Bing, Black Republican, Red Sweet	Western cherry fruit fly (*Rhagoletis indifferens*)	Surround (95% kaolin) Cocoon (100% hydrous kaolin), Eclipse (>75% limestone), Purshade (62.5% limestone).	Deterred landing and oviposition	Reduced landing and ovipositon over the fruit surface.	Yee (2012)
Blue berry	Patriot	Blueberry maggot (*Rhagoletis mendax*)	Surround ® WP	Reduced oviposition	Weekly application of surround reduced the oviposition scars pronouncedly.	Lemoyne et al. (2008)
Olive	Ziety, Djlt	Fruit fly (*Bactrocera oleae*)	M-99-099	Reduced infestation and suppressed population	Suppressed the population and provided season-long insect control	Saour and Makee, 2004
	Carolea	Olive fruit fly (*Bactrocera oleae*)	Surround WP	Reduced infestation	Significant reduction in fruit infestation levels without effecting nutritional	Perri et al. (2005)

					and sensory qualities.	
Persimmon	Triumph	Medfly (*Ceratitis capitata*)	Surround ® WP (6%)	Repellence and Camouflaging	Application of kaolin particle film resulted in practically clean fruits than the control.	Mazor and Erez (2004)
Grape	Flame Seedless Chardonnay Thompson Seedless	GWSS-Glassy Winged Sharp Shooter (*Homalodisca coagulate*)	Surround WP	Repellence, Camouflaging	Reduced the number of adults and their oviposition. Controlled transmission of *X. fastidiosa*, which cause Pierce's disease	Puterka et al. (2003)
	Thompson Seedless, Flame Seedless, Chenin Blanc	GWSS-Glassy Winged Sharp Shooter (*Homalodisca coagulate*)	Kaolin, Harpin and Imidachloprid	Reduced infestations and increased mortality	Higher mortality rate of GWSS on particle film coated vines	Tubajikaa et al. (2007)
Pistachio nut	Red Aleppo	Pistachio psyllid (*Agonoscena targionii*)	Kaolin particle film	Reduced nymph density	Suppressed psyllid nymph damage	Saour (2005)
Weeping fig	–	Thrips (*Gynaikothrips uzeli*)	Surround WP	Repellence	80% reduced galls in laboratory tests and 74% reduction in field tests.	Held et al. (2009)
B. Vegetable crops						
Potato	Red LaSoda	Potato Psyllid (*Bactericera cockerelli*) vectoring 'Zebra Chip' disease	Purshade (limestone) Apogee (Prohexadione-Ca)	Repellence and reduced oviposition	Significant reduction in oviposition	Prager et al. (2013)
Tomato	HLY 19 *hp* (high pigmented)	Insects	Surround® WP	Repellence	Reduced insect damage by 79%	Cantore et al. (2009)
	Florida Lanai	Potato psyllid (*Bactericera cockerelli*)	Surround® WP	Non-preference	Laid less number of eggs on the treated leaf surface.	Peng et al. (2011)
Cabbage	Fiesta	Polyphagous aphid (*Myzus persicae*)	F-01-KV-6	Non-preference	No significant effect on survival, growth rate and reproduction.	Barker et al. (2007)
Onion	Millenium	Onion thrips (*Thrips tabaci*)	Surround® WP	Reduced oviposition and hatching rate	Developmental stages were longer & mortality rates were higher	Larentzaki et al. (2008)
Pea	W6-15368	Pea aphid (*Acyrthosiphon pisum*)	M96-018 (hydrophobic) Surround® WP (Hydrophilic)	Repellence	Hydrophobic film reduced the infestation rate while the hydrophilic films have no effect on aphid population	Eigenbrode et al. (2006)
Egg plant	Millionare	Flea beetle (*Epitrix* spp.)	Surround® WP	Reduced damage and infestation	Increased the total marketable yield.	Maletta et al. (2004)
Melon (Cantaloupe)	ImPac	Silverleaf whitefly (*Bemisia argentifolii*)	Surround® WP Sun spray oil (Mineral oil)	Repellence	Significantly reduced the number of eggs and adults	Liang and Liu (2002)
Chile pepper	B18	Beet leaf hopper (*Circulifer tenellus*)	Surround® WP (3%)	Repellence	Suppressed beet curly top virus transmitted by beet leaf hopper.	Creamer et al. (2005)
Calabrese	*B. oleracea italica cv.* Fiesta	Diamond back moth (*Plutella xylostella*)	F-01-KV-6	Non-preference/repellence	Significantly reduced survival to adulthood and increased the development time	Barker et al. (2006)
Collards	–	*Bemesia argentifolii*	M96-018 + MeOH, surround® + M03	–	No control	Poprawski and Puterka (2002a)
Pepper	Capistrano	*Bemesia argentifolii*	M96-018 + MeOH, surround® + M03	–	No control	Poprawski and Puterka (2002b)

(2005) found that kaolin treatments (using Surround) suppressed BCTV (beet curly top virus) on Chile pepper in New Mexico. Tubajikaa et al. (2007) evaluated the incidence of Pierce's disease (*Xylella fastidiosa*) on kaolin particle sprayed grape vines and found reduced incidence of 6% in kaolin treated plants compared to 19% in control plants (non-sprayed).

7.6. Solar injury

High solar radiation during the summer season results in excessive light and heat load on leaves and fruits. Although the relative contribution of heat and light stresses to solar injury is not clearly established, yet it is caused extensively by the interaction of high temperature and light (Glenn et al., 2002; Schrader et al., 2003; Schrader, 2011). Usually, prolonged exposure of leaves and fruit to UV radiation can result in solar injury, which degrades chlorophyll and damages the plant photosynthetic system (Glenn et al., 2008). The characterized reduction in chlorophyll a and b is due to photo-bleaching and an increase in chlorogenic acid and carotene concentrations, which serves as a possible protection mechanism for plants (Wunsche et al., 2001). Chlorophyll has been reported to decrease due to solar injury in all the apple cultivars studied by Felicetti and Schrader (2009).

Dark green fruit are more sensitive to solar injury than red or yellow fruit, because chlorophyll undergoes photo-oxidation, which is an essential process for solar injury development (Rabinowitch et al., 1983). Furthermore, higher sugar levels, may render the fruit more susceptible to solar injury. Sugar levels rise in fruit towards harvest and susceptibility to solar injury concomitantly increases towards harvest. Similarly, water stress can predispose fruit to sunburn or aggravate existing damage (Schrader et al., 2003). The evaporation of water from the fruit peel surface extracts energy, which in turn cools the peel surface as water stress negates evaporative cooling, resulting in an increase in fruit temperature (Woolf and Ferguson, 2000).

Cultivar and its growing habit, rootstock (dwarf or vigorous) used, position of fruit on tree, number of fruit per cluster, cool weather prior to high temperature, competition for assimilates, sudden exposure of fruit from a low light environment to high irradiance and low humidity are some factors which may also have significant role in solar injury to fruit (Jones et al., 1992; Warrington et al., 1996; Van den Ende, 1999; Yuri et al., 2000; Awad et al., 2001).

Schrader et al. (2003) has characterized solar injury into three distinct types, namely sunburn browning, sunburn necrosis and photo-oxidative sunburn. Sunburn browning is the most predominant and economically important characteristics to apple producers (Felicetti and Schrader, 2008). It results from the simultaneous exposure of the apple fruit to high irradiance and high temperatures. Fruit peel temperatures of 46–49 °C in the presence of light, particularly UV-B are required for manifestation of the symptoms of sunburn browning (Schrader et al., 2003). The symptoms appear as yellow, brown, tan or golden bronze-discolored patches on the affected fruit peel. Although sunburn browning affects the fruit surface and its subsequent appearance, it does not cause fundamental damage to the epidermal tissue and can be seen as an adaptive process. Sunburn necrosis is mainly caused by excessively high temperatures (52 ± 1 °C) (Schrader et al., 2001).

The extreme heat causes thermal death of epidermal and sub-epidermal tissue and the formation of necrotic spots on the affected fruit area. Sunburn necrosis alters the structure of membranes and thyalakoids, resulting in electrolyte leakage. Photo-oxidative sunburn occurs when initially shaded fruit are suddenly exposed to high irradiation (Schrader et al., 2008). This type of solar injury may occur at temperatures below 30 °C but UV-B does not seem to have any role causing this form of solar injury. It can cause heavy losses (Colavita, 2008), and sometimes complete crop loss at times of extreme heat. In addition, fruit quality is greatly affected by the solar injury (Volz et al., 1995; Racsko et al., 2005: Schrader et al., 2009).

Plants use several protective mechanisms to avoid sunburn, i.e., by i) dissipation of excess energy through the xanthophyll cycle (Demmig-Adams et al., 1995; Muller et al., 2001; Ma and Cheng, 2003), ii) induction of antioxidants (e.g., various phenolics, flavonols and proteins) to minimize oxidative damage (Mackerness and Thomas, 1999; Merzlyak and Solovchenko, 2002; Ma and Cheng, 2003; Solovchenko and Schmitz-Eiberger, 2003), iii) UV-B attenuation by UV-B-absorbing/reflecting pigments (Mackerness and Thomas, 1999; Merzlyak and Solovchenko, 2002), and iv) production of heat shock proteins (Burke and Orzech, 1988; Ritenour et al., 2001).

The inadequacy of resistance mechanisms and the high susceptibility of fruit to solar injury suggest the need for an external intervention to reduce it in fruit, and hence, several methods are being used to lower the light levels to which the fruit are exposed and thus reducing peel temperatures. For example, shade netting may lower the incidence of sunburn to 1% and also decrease red blush development (Smit, 2007), making it the most effective technique. The major drawback of shade netting is that it is also the most expensive method (Smit, 2007). Other techniques to reduce sunburn include evaporative cooling and spray application of particle films.

Evaporative cooling entails the wetting of fruit with overhead sprinkles in order to decrease peel temperature (Unrath and Sneed, 1974; Parchomchuk and Meheriuk, 1996). Particle films consisting of white clay minerals, e.g., 'Surround', or natural lipids, e.g., 'Raynox', reflect visible or UV radiation (Glenn et al., 2002) are successful in reducing peel temperatures and solar injury significantly (Glenn et al., 2002; Schupp et al., 2002, 2004), and are more affordable than evaporative cooling, and effective in reducing the occurrence of solar injury in several fruits and vegetables (Sibbett et al., 1991., Gindaba and Wand, 2005; Glenn et al., 2002; Schupp et al., 2002; Le Grange et al., 2004; Melgarejo et al., 2004; Gindaba and Wand, 2008., Schupp et al., 2004; Wunsche et al., 2004., Schrader et al., 2008) (Table 3). Thus, use of particle films will reduce the dependence of agriculture on irrigation water sources to mitigate heat stress. Particle films can become a key component of heat damage control as water shortages and conservation measures become key environmental issues.

7.7. Heat stress

Heat stress is a limiting factor for plant productivity; sometimes even the mild climate zones experience certain periods of high temperatures, due to the prevailing climate change. Fruit losses from heat stress typically occur when the temperature increases rapidly and the fruit have not been acclimatized. Heat stress can also cause significant losses which include fruit drop, reduced size, overall quality, storage life, and reduced bloom in the following season. Particle films can lower apple peel temperatures by 6 °C to 8 °C, while leaves are typically 3 °C to 5 °C cooler. Kaolin-based particle films have demonstrated that the reflective nature of the resulting plant surface can increase plant productivity (Glenn and Puterka, 2005) primarily by reducing temperature in fruit (Glenn et al., 2002, 2005; Wand et al., 2006), leaf (Glenn et al., 1999, 2001b; Thomas et al., 2004), and canopy (Glenn et al., 2003) in apple; fruit in pomegranate (*Punica granatum*) (Melgarejo et al., 2004) and tomato (*Lycopersicon esculentum*) (Saavedra et al., 2006; Pace et al., 2007), and leaf in coffee (*Coffea arabica*) (Steiman et al., 2007) and grapefruit (*Citrus paradisi*) (Jifon and Syvertsen, 2003).

Application particle film has increased the yield by decreasing pre-harvest fruit drop in 'Seckel' pear (Puterka et al., 2000b). It was noted that applying a reflective coating to plants under water stress provides more benefit in reducing heat stress than reduction in potential photosynthesis (Glenn et al., 2001b). Reducing the heat stress can actually increase net photosynthesis, when Surround was applied early in the season. Normally plants under heat stress will shut down photosynthesis whereas reducing heat stress will allow the plants to continue to photosynthesize until the later part of the day. Shellie and Glenn (2008) observed that kaolin coating reduced wine grape leaf

Table 3
Effects of particle films on sunburn in fruits.

Crop	Cultivar	Remarks	Reference
Apple	Fuji, Scarlet Delicious, Royal Gala, Braeburn, Imperial Gala.	Suppressed solar injury with 3–12% processed-kaolin particle film concentration.	Glenn et al. (2002)
	Fuji, Honey Crisp	Reduced sunburn	Schupp et al. (2004)
	Braeburn	Reduced fruit surface temperature by 20% thus reducing sunburn significantly.	Wunsche et al. (2004)
	Granny Smith, Fuji	Significant reduction in sunburn	Wand et al. (2006)
	Anna	Reduced incidence of sunburn	Aly et al. (2010)
	'Fuji', 'Granny Smith' and 'Royal Gala'	Significant reduction in sun burn	Le Grange et al. (2004)
Pear	'Packham's Triumph' (PT) and 'Beurre d'Anjou' (BDA).	Reduced sunburn by 67–82% and 74–91% in PT and BDA respectively.	Colavita et al., 2011
Pomegranate	Mollar de Elche	Sunburn damage was reduced from 21.9 to 9.4%	Melgarejo et al. (2004)
	Wonderful	Reduced sun damage	Weerakkody et al. (2010)
Grape	Cabernet Sauvignon	Reduced cluster damage caused by sunburn	Smith (2005)
Melon	Crenshaw	Suppressed solar injury with an 8 °C reduction in surface temperature.	Lipton and Matoba (1971)
Tomato	HLY 19 *hp* (high pigmented)	Reduced sunburn by 96%	Cantore et al. (2009)

temperature under different irrigation regimes. However, it showed reduction in stomatal conductance and less negative leaf water potential values under well-watered conditions only. Lack of response to kaolin under deficit water conditions was probably due to a water-stress-induced increase in stomatal closure that was independent of leaf temperature.

Processed kaolin particle films reduced environmental stress in 'Empire' apple by reducing canopy temperature. It also increased mean fruit weight and red color (Glenn et al., 2003). The season-long application of Surround WP reduced fruit cracking in 'Stayman' apples compared to untreated trees. Lombardini et al. (2005) treated pecan trees with kaolin-based particle films which reduced the leaf temperature by 0–2 °C than the air temperatures, compared to 4–6 °C for control leaves. Particle film treatments reduced radiation and heat load on exposed 'Empire' apple leaves enabling them for better regulation of leaf temperature and improved light distribution inside the canopy resulting in increased carbon gain at the whole plant scale (Glenn, 2009). Kaolin also reduced rose leaf temperature by 2.5 °C approximately at midday compared to plants non-sprayed with kaolin (Cuitiva et al., 2011). Application of 10% processed kaolin particle film on papaya leaves showed higher light reflection and lowered the leaf temperatures during the peak hot period from 12 pm and 2 pm (Campostrini et al., 2010). Kaolin clay particles had a significant positive effect on olive leaf water content, succulence, leaf tissue density and leaf temperature under both drought and well irrigated conditions (Denaxa et al., 2012).

7.8. Freeze protection

In certain species, freeze damage to sensitive crops can only occur after the formation of ice in the plant tissues. While the universal melting point of frozen plants is close to 0 °C, studies on various crops have demonstrated that the freezing point of different plants varies and the degree to which this occurs is termed the supercooling ability (Chen et al., 1995). The amount of super-cooling in turn depends on the presence and activity of ice nucleators which can either be extrinsic, such as the ice nucleating bacterium, *Pseudomonas syringae* (Lindow, 1995), or intrinsic compounds of plant origin (Ashworth et al., 1985).

There is still doubt regarding the exact nature and importance of these natural freezing events. There are several reports of the importance of surface water leading to early ice nucleation of plants (Fuller and Le Grice, 1998; Fuller and Wisniewski, 1998) suggesting that free water facilitates the activity of ice nucleators present in the phylloplane. Le Grice (1993) confirmed that, the surface water was the most important aspect with regard to early freezing and subsequent freeze injury in early potatoes. In most field situations, dew fall precedes freezing ensuring that leaf surfaces are nearly always wet prior to freezing (Pescod, 1965).

Protection of sensitive crop plants from freeze damage has always been a major challenge to horticulturists. Major damage occurs during radiative freezing conditions in spring when physiological cold hardiness has been lost (Fuller and Le Grice, 1998; Fuller and Telli, 1999). Various field techniques are employed in crops which generally involve interfering with the freezing environment by the use of turbines to mix cold and warm layers of air or by smoke blankets to prevent the loss of long wave radiation by the crop (Kalma et al., 1992). In some cases, crops are sprayed with a continuous fine mist of water which freezes on the plant and raises the leaf temperature to zero by the release of the latent heat of freezing of the water (Hamer, 1986, 1989). In this strategy, care must be taken to keep the mist continuous so that the leaf surfaces remain at zero and, although it is encased in ice, the leaf does not actually freeze. A risk of this technique is that the ice on the plant can build up so extensively that it causes physical damage to the plant such as branches snapping on fruit trees.

Application of field formulated compounds against frost protection has been an elusive dream of many researchers and agri-chemical companies. Many compounds have been screened and some have been reported in the literature for fruits and vegetables (Wilson and Jones, 1980; Wilson and Jones, 1983a,b). However, exogenously applied cryoprotectants, such as sorbitol or polyethylene glycol, appear to be phytotoxic at active concentrations or only marginally effective in controlling ice nucleation in vegetative field crops. Glenn et al. (1998) reported biologically active properties of hydrophobic and hydrophilic kaolin dust formulations. Wisniewski et al. (2002) reported the use of a hydrophobic kaolin as a protectant of freezing in tomato where it blocked the effect of ice nucleating bacteria and allowed whole plants to super cool to −6 °C, despite the presence of frozen droplets on the leaf surface. Fuller et al. (2003) assessed the frost damage to potatoes, grapevine and citrus plants treated with an acrylic polymer (Antistress™) and with a hydrophobic particle film (CM-96-018) separately just prior to freezing. Interestingly, the hydrophobic particle film reduced freezing injury in the treated plants.

In large freezing tests, the application of the hydrophobic particle film consistently led to less damage, while the acrylic polymer led to the same or more damage compared to control plants. Detailed examination of the freezing leaves of all three species using infrared thermal imaging revealed that the hydrophobic particle film delayed the entry of ice from a frozen water droplet containing ice nucleating active bacteria and in some cases for the complete duration of the frost test (Fuller et al., 2003). In contrast, the acrylic polymer was only able to influence the time of ice nucleation of the leaves of citrus plants. Thus, the hydrophobic particle film showed considerable promise as a frost protectant applied to susceptible crops just prior to occurrence of freezing.

7.9. Leaf gas exchange

Till date limited information is available about the effect of kaolin particle film application on gas exchange of (adaxial, abaxial, or both) leaf surface. Kaolin based films form a white, reflective physical barrier called a 'particle film' on the plant surface. Although designed not to interfere with leaf gas exchange, the findings to this end are mixed (Glenn and Puterka, 2005). Differences in product application, climatic conditions, crop or cultivar, and physiological state of the plants may account for some of the disparity between these findings. Available information suggests that particle films favor gas exchange under conditions of environmental (high temperature) and physiological (drought) stress (Glenn et al., 2001b).

In 'Ginger Gold' apple, greater rates of net photosynthesis (Pn) were achieved at a higher frequency of kaolin particle film application especially when leaf temperatures exceeded 35 °C (Prive et al., 2007a,b). Wunsche et al. (2004) found reduced gas exchange at the leaf level but no effect of PF on canopy gas exchange. They attributed this paradox to improved light distribution within the canopy, yet Glenn and Puterka (2007) demonstrated that interior canopy light levels are increased by PF applications. Rosati et al. (2007) modeled light absorption and distribution within walnut and almond trees with and without a kaolin PF to understand the paradox and demonstrated that although there is an 20% reduction of photosynthetically active radiation (PAR) to the photosynthetic apparatus in the individual leaf, this radiation was effectively redistributed within the interior canopy to increase the interior canopy photosynthetic rate, resulting in an estimated 9% increase in canopy photosynthesis. Similarly, whole canopy gas exchange studies of 'Empire' apple coated with particle film showed an increase in carbon assimilation and transpiration (Glenn, 2010).

7.10. Water use efficiency

Under conditions of high temperatures in combination with or without high intense solar radiation, which favor water loss through transpiration, the water use efficiency (WUE) is enhanced. However, processed kaolin particle films reduced water use efficiency when sprayed over the leaves of apple cv. Empire; likely due to increased stomatal conductance associated with reduced leaf temperature (Glenn et al., 2003; Glenn, 2010). Basnizki and Evenari (1975) applied a reflectant coating to globe artichoke (*Cynara scolymus* L.), which reduced leaf temperature, increased water use efficiency, and increased plant survival. Rao (1985) applied kaolin films to non-irrigated tomato (*L. esculentum* Mill) and demonstrated that the reflective kaolin improved the water status and yield of non-irrigated plants compared to the non-treated controls. In wine grape, application of kaolin particle films enhanced water use efficiency (WUE) under non-limiting soil moisture conditions due to closure of stomata and increased leaf water potential (Glenn et al., 2010).

7.11. Carbon assimilation

When applied over the crop surface, the particle film transmits 90–98% of photosynthetically active radiation (PAR), while its reflective properties reduce heat build-up, ultraviolet radiation damage and heat stress in plant canopies. These properties ultimately produce more efficient photosynthesis, and thus increase the amount of carbon assimilates available for fruit development (Glenn et al., 1999). Earlier work focused primarily on crop yield, which has suggested that particle film applications, in some crops and under certain conditions, increased yield in tomato (Srinivasa Rao, 1985), peanut (SoundaraRajan et al., 1981) and apple (Glenn et al., 2001b). However, all studies on particle films were not unanimous in its positive response.

Some studies indicated no/minimal effect of particle films on carbon assimilation at the leaf level in apple (Gindaba and Wand, 2005; Gindaba and Wand, 2007a,b), pecan (*Carya illinoinensis*) (Lombardini et al., 2005), pepper (*Capsicum* spp.) (Russo and Diaz-Perez, 2005), walnut (*Juglans regia*), almond (*Prunus dulcis*) (Rosati et al., 2006), and beans (Tworkoski et al., 2002); whereas some others reported significant reduction in carbon assimilation with PFs at the leaf level (Le Grange et al., 2004; Wunsche et al., 2004) which they attributed primarily to the reduced light at leaf surface, but none of these studies have linked leaf level responses to plant yield. The work by Glenn et al. (2001b, 2002) suggested that under excessive heat conditions (air temperatures above 30 °C), the kaolin applications reduced temperature, and thereby increased carbon assimilation and stomatal conductance. However, in one of their trials where midday air temperatures remained below 25 °C, leaf carbon assimilation was reduced, due to a reduction in light penetration to the leaf surface (Glenn et al., 1999). Thus, they concluded that under these conditions, carbon assimilation was limited by low light levels rather than excessive heat.

Wunsche et al. (2004) found reduced gas exchange at the leaf level but no effect of PF on canopy gas exchange. They attributed this paradox to improved light distribution within the canopy. Glenn and Puterka (2007) demonstrated that interior canopy light levels are increased by PF applications. Kaolin affected the photosynthetic response of almond and walnut leaves to the photosynthetically active radiation (PAR): kaolin-coated leaves had similar dark respiration rates and light-saturated photosynthesis, but a higher light compensation point and lower apparent quantum yield, while the photosynthetic light-response curve saturated at higher PAR. When Rosati et al. (2006) used these parameters to model the photosynthetic response curve to PAR, it was estimated that the kaolin film allowed 63% of the incident PAR to reach the leaf.

The particle film significantly reduced carbon assimilation (A) in the inner canopy under both moderate and high leaf-to-air vapor pressure deficit (VPD) but there was reduced A in the outer canopy only under moderate VPD when stomatal conductance was high. Apparent quantum yield of leaves on the outer canopy of treated trees was reduced, possibly indicating that coated leaves reflected more light, and thus have less light available for photosynthesis than uncoated leaves under the same external light intensity (Le Grange et al., 2004).

Application of particle film unaffected the leaf net assimilation rate, stomatal conductance and stem water potential in pecanut cv. Pawnee (Lombardini et al., 2005). In tomato, net assimilation at leaf scale was reduced by 26% in kaolin-coated treatments. Stomatal conductance decreased by 53%, resulting in reductions of 34 and 15% in transpiration and internal CO_2 concentration, respectively. In kaolin-treated plants, assimilation and evapo-transpiration rates were reduced by 17 and 20%, respectively, while dark respiration remain un-affected (Cantore et al., 2009). Steiman et al. (2007) observed the photosynthesis of coffee plants sprayed with kaolin was 71% greater than full-sun plants in the second year of application and yields were doubled.

Campostrini et al. (2010) applied 10% foliar processed-kaolin particle film over 'Golden' papaya leaves and found that it did not affect net CO_2 assimilation rates, stomatal conductance and transpiration; although the light reflection was higher and the temperature on the leaves was significantly lowered in the plants that received the particle film coating. Denaxa et al. (2012) applied glycine betaine and kaolin clay particles to drought stressed olive trees, which resulted in increased CO_2 assimilation rates compared to control. Furthermore, kaolin clay particles treated leaves exhibited high diurnal CO_2 assimilation rates under drought conditions.

7.12. Fruit maturity, yield and postharvest quality

Kaolin particle film may also influence fruit maturation and internal quality. There have been reports of delayed maturation in some trials (Glenn et al., 2001b; Erez and Glenn, 2004). However, apple fruit internal quality characteristics and ripening processes were not influenced by Surround WP applications in many studies (Brown et al., 2001; Glenn et al., 2001b; Schupp et al., 2002, 2004). Glenn et al. (2005) noticed no effect of particle films on 'Fuji' and 'Honey Crisp' cultivars of apples. Application of kaolin based films significantly delayed fruit maturation in peach with increased fruit size and soluble solids (Lalancette et al., 2005). Apple fruit with kaolin based reflective ground covers ripened 2–3 days earlier without affecting internal fruit quality and sugar as indicative of taste (Meinhold et al., 2011), while the maturity was significantly delayed in 'Anna' apples (Aly et al., 2010).

Kaolin treatment improved fruit color of 'Granny Smith' and 'Royal Gala' apples, and also delayed starch conversion in 'Granny Smith' at harvest and during the early storage period but not thereafter (Wand et al., 2006). Incidence of water core at harvest was significantly reduced by kaolin treatment, but this disorder disappeared during cold storage in both treatments. There were no effects on peel anthocyanin or phenolic concentrations in any cultivar compared to unsprayed fruit (Wand et al., 2006). 'Fuji' apple had showed greater fruit weight and soluble solid content while 'Cameo' had shown greater soluble solids, higher starch indices and greater red color in Washington with the application of particle films (Glenn et al., 2005).

Kaolin film coated, biodegradable paper (UniSet O™) enhanced maturity of 'Gala Mondial' apples by 2–3 days and improved the proportion of well colored class I fruit without affecting internal fruit quality and sugar as indicative of taste (Meinhold et al., 2011). Similarly, 'Galaxy' apple fruits coated with the kaolin particle film had the highest appearance rating, but also exhibited the lowest smoothness rating due to film residue (Ergun, 2012).

PF treated 'Cabernet Sauvignon' grape exhibited increase in berry weight, berry juice, malic and citric acid along with increases to sucrose and glucose concentrations (Cooley et al., 2008). Total amount of berry anthocyanins were increased by PF application (Ou et al., 2010), yet Song et al. (2012) noticed no influence of PF on 'Merlot' grape. In tomato, kaolin treatment increased lycopene content by 16%, but did not affect total soluble solid content, fruit dry matter, juice pH, titratable acidity or tomato fruit firmness (Cantore et al., 2009).

8. Removal of particle films from fruits

Particle film coating on fruit surfaces may be considered unsightly for consumers. Hence, washing of the fruits is necessary immediate after harvest. Particle films are designed to have controlled adhesion to fruit surfaces during the season. A wash is required in order to remove the particle residue on the edible parts of the treated plant. Brushes with or without washers, can be used for this purpose. For fresh market, fruit that are not to be washed, the applications of particle films should be stopped when fruits are still small — about 1/4 to 1/3 of eventual size. The remaining coating will eventually loosen and fall off as fruit grows or from rain or wind attrition (Glenn and Puterka, 2004). For delicate fruits (e.g., table grapes), applications of particle films should be stopped before bloom. Of several PFs, Surround WP is easily removed during processing in wineries and olive oil industries.

Particle film treated fruit or vegetables for the fresh market are cleaned after harvest by washing, rinsing, and waxing processes. Growers should conduct small scale trials to ensure that existing dump tanks, brushes and rinsing systems will remove particle film satisfactorily. An approved cleaning detergent can be added to the dump tank to improve cleaning efficiency. Some growers have increased the time in the dump tank, changed brush length or shape and increased pressure on rinses to improve the film removal process (Glenn and Puterka, 2005). Traces of particle films do not affect the quality of processed fruit. However, particle films should not be used on crops intended for the fresh market or field packed crops unless provision is made to wash the film from the product.

Particle films can be washed off easily from harvested apples, pears, plums and nectarines with standard packing shed cleaning systems, including soak-tank, long brush bed and overhead pressure sprayers. Waxing procedures also improve fruit appearance. Some pack house managers have found it beneficial to use warm water (28 °C) and soak fruit slightly longer than normal and/or to add an approved fruit washing detergent before brushing. If some residue remains in the stem and calyx end of the fruit, waxing will render it essentially invisible. A pack house film removal test is required prior to its commercial use to ensure that the packing line can successfully remove all of the film. Careful attention must be paid to the washing instructions on the product label before use.

Some growers use Surround®/Eclipse® early in the season, but then switch over to wax-based Raynox® because the water tends to wash off the other products. There has been some concern that applying Raynox® on top of the particle products might seal the residues so they can't be removed. But, the research showed that wasn't the case (Schrader, 2011). Fruit Shield®, which was difficult to see in any case, was particularly easy to wash off. The white products (Surround® and Eclipse®) left persistent residues in the stem bowls. Immediately after the fruit came off the brush bed, the stem bowls and calyx area were wet and they looked clean, but as they dried, the residues became very visible again (Warner, 2006).

9. Conclusions

The particle film technology, based on the mineral particle kaolin, is really a boon to the farmers/growers who wish to transform from conventional agricultural techniques to organic cultivation practices and/or integrated management practices. This technology aims in regulating the conventional chemical pesticides used for food production, thus reducing the pesticide load over the environment, which in turn, will improve agricultural worker safety, and insure a safer food supply for the consumer.

The unique benefit of this technology is that, the insect pests are less likely to develop resistance; and thus, particle films will be useful in resistance management programs. Particle films create a physical barrier that repels insects and hence there is no toxic selection pressure. The international adoption of particle film based insect control programs, have reduced the use of chemical pesticide at global level and thus ensured the availability of produce with reduced levels of pesticides to the consumers. Particle films will also reduce the dependency of agriculture on irrigation water by increasing the water use efficiency (WUE) and by replacing the evaporative cooling technique used for reducing sunburn and heat stress in some horticultural crops.

The multifaceted aspects of particle film technology for agri/horticulture will have a global impact on many aspects of the world agricultural production systems. Thus, particle film materials are a valuable multifunctional new tool to suppress diseases and repel insects while providing heat stress reduction in tree fruit production. Due to their unique nature, they have been registered for use in agriculture with a pre-harvest interval of zero days.

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