Chapter 7

Detergents and Soaps as Tools for IPM in Agriculture

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Additional information is available at the end of the chapter

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Abstract

This chapter presents extensive and updated knowledge from scientific and technical reports on the management of agriculture pests using detergents and soaps (D + S), with emphasis on their utility in integrated pest management (IPM) schemes. It includes a review on their environmental, ecological, and toxicological impacts, and their possibilities to become important tools for pest control, especially for those D + S having minimum risk, considering both current and newer products. The present knowledge of their modes of action on arthropods is addressed, revealing the need to better identify the mechanisms to optimize their use against crop pests. Their disadvantages are also analyzed, mainly the lack of residual effect and the potential toxicity to plants. Some ways these problems have been overcome are presented. A comparison of the direct costs of the use of conventional pesticides versus D + S, achieving statistically similar levels of control, is discussed, and scenarios where detergents are competitive (representing lower costs) are presented. There is also a review of the type of compounds reported in the specific literature, which leads to highlight the opportunities to develop agriculture detergents and soaps suited to local agriculture needs. New findings on D + S as co-adjuvants for conventional and biological pesticides, and their potential utilization as safe postharvest treatments against pest, are also presented. Finally, the authorization for soaps and detergents is also discussed, highlighting the need for a joint effort (state agencies, producers, researchers, etc.), in order to increase the offer and the use of detergents and soaps, partially replacing conventional pesticides, to take advantage of their potential as sustainable pest management tools, particularly for IPM programs, but also for organic and conventional productive schemes.

Keywords: detergents, IPM, soaps, surfactants, sustainability, toxicity

1. Introduction

1.1. Chemical control in integrated pest management (IPM) programs and detergents and soaps

Integrated pest management is a strategy developed to control agricultural pests and, at the same time solve problems derived from the extensive and intensive implementation of chemical control in conventional agriculture, where broad spectrum, specific action site, and persistent pesticides are used. Compounds with this profile have been called "conventional pesticides" and are responsible for causing resistance in pest populations, destruction of beneficial arthropods, and presence of pesticide residues in foods, soils, water, and air [1]. In order to obtain an economic, environmental, and ecologically sustainable food production, IPM encompasses several components, including cultural, biological, and chemical control [2]. Therefore, the use of pesticides is not excluded from IPM programs, for instance, when there is no other available tools to avoid economic damage [3], synergy occurs between chemical and biological control [4], or a diverse pest complex affects the crop [5]. Under those circumstances, the products used should target several sites and mechanisms (multisite), be shortly persistent in the environment and crops (non-residual), and have both a narrow spectrum (selective) and low toxicity to mammals. Many compounds having these attributes have been called "alternative pesticides", including oils, pheromones, botanicals, entomopathogens, and soaps and detergents, among the most frequently used [6, 7]. For definition purposes, agriculture detergents and soaps, from now on "D + S", correspond to surfactants from either natural or synthetic origin, formulated specifically for pest control or other uses in crops. Within these options, D + S have additional particularities, being relatively inexpensive, easy to produce and apply, versatile (controlling juvenile and adults), allowed as postharvest treatment, etc. [8, 9].

1.1.1. Resistance management

Resistance is a consequence of the elimination of susceptible genotypes and selection, over time, of the tolerant part of the population by the frequent and wide use of pesticides with specific sites of action that lose afterwards their capability to control pests [1]. The alternating use of conventional products with different action sites has been one way to face resistance, but a more holistic approach is necessary to provide a sustainable solution [10]. That is why IPM was developed during the second half of the twentieth century, attempting to either avoid or reverse resistance by replacing chemical control by other strategies, and/or by using several different chemicals with multiple modes of action, as D + S that, therefore, should become useful tools for IPM [8, 11].

1.1.2. Environmental, ecological, and toxicological issues

Environmental contamination, diversity threatening, and toxic effects on mammals and other animal species are well known and severe impacts from the use of conventional pesticides. Environmental toxicity by soaps, on the other hand, is considered very low [12], but detergents in wastewater (sometimes in large concentrations) are considered important pollutants when

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they reach rivers and streams, where they form foam layers and affect the aquatic fauna. However, the greater biodegradability of current surfactants has significantly reduced those problems [13]. Besides, sprays in farms should not massively reach water courses, therefore minimizing the potential impact in surface and groundwater. Based on studies of wastewater used for irrigation [14], some surfactants alter physical, chemical, and biological properties of some types of soils [15]. However, linear alkylbenzene sulfonates (LAS, widely used in detergents) are considered not to be a threat to terrestrial ecosystems on a long-term basis because of biodegradation [16], although nonylphenol has been questioned [17]. Thus, their impact depends largely on the type of surfactant chemistry, providing room for testing, selecting, and using those less hazardous products.

In general, D + S have low acute toxicity [18], particularly non-ionic or anionic detergents, which are, by far, less dangerous than conventional insecticides [19]. For instance, the soap Safer has an oral LD_{50} of 16.500 ppm (= median lethal dose, i.e., the amount of active substance per body weight required to kill half of an exposed population), which is by far less dangerous than conventional insecticides, including botanicals [12]. The risk should be even lower considering both the necessary dilution and the small chance of ingestion. Conventional pesticides on the foliage are an important risk for applicators by dermal exposure, making necessary reentry intervals after their application, which are not needed when D + S are used. Detergents can cause dermal [20] or eye irritation, but in general this type of exposure represents a very low risk to agriculture workers wearing the basic personal protective equipment, although some respiratory disorders have been reported to detergent exposure, mainly on asthma sufferers [21, 22]. There are some concerns regarding specific housecleaning products (e.g., those containing alkyl phenols), which have been related to breast cancer [23], although under normal exposure in the field the risks are reduced, since no systemic toxicity is expected for most D + S and several components of their formulations [18, 19, 24], but this issue needs a case-by-case analysis. Another important issue is the persistence of conventional pesticide residues in/on the marketable part of the crop that makes necessary to establish regulations of MRLs (maximum residue limits) for foods. Thus, PHIs (preharvest intervals) are established to comply with the law, whereas most D + S are not subjected to this type of restrictions. In fact, some D + S are applied right before harvest [9] and others are authorized for postharvest treatments [25], being easily washed off from the epidermis of fruits and vegetables by rinsing before consumption, having minimum risk and being therefore exempt of MRLs [26].

Regarding the impact on beneficial fauna in crops, D + S have been considered more selective than conventional insecticides, being compatible with biological control due to their low adverse impact on not sprayed insect and mites and the lack of residual activity [4, 27]. The only threat occurs by the direct spray or when the solution persists on the foliage, usually for short periods, killing predators and parasitoids. Therefore, the release of beneficial arthropods after a spray, once deposits are dry, allows them to survive. Available EIQ (environmental impact quotient that considers environmental and ecological threats) values for soaps indicate their low impact (e.g., 19.45 for M-Pede), close to most botanicals or IGRs (insecticide growth regulators), and smaller than those of horticulture oils [28]. However, no data on detergents were available. Therefore, research to identify efficient (current or new), but also nontoxic and ecologically safe D + S for pest control is required.

1.1.3. Legal and economic issues

Conventional pesticides are subject to a complex and expensive registration process where, after agronomic and toxicological reviews, they might obtain legal authorization to be used on crops. On the other hand, D + S are not necessarily subjected to registration, since some products are not labeled as pesticides, but as tree cleaners. However, it is important to transparent the real purpose of its use in agriculture [11]. Even when explicitly recommended to control pests, D + S should be easier to register after considering their risk assessment due to their low acute and chronic toxicity and, in some cases, their status as food additives or edible surfactants [29]. Considering the growing demand for residue-free foods, the eventual replacement of conventional pesticides for D + S will make those foods preferred by customers, increasing their value and making their trade easier. Therefore, all the actors involved should deeply assess D + S uses for pest control.

1.2. Modes of action of detergents and soaps as pesticides

The modes of action for D + S against pests have not been well understood yet [30, 31]. In fact, D + S are not considered on the IRAC (Insecticide Resistance Action Committee) lists that classify the pesticides mode of action for those with known specific target sites [32]. This is because D + S are not known to act at specific target sites, but at multiple sites [11]. Despite that, wax removal, arthropod dislodging, and drowning have been mentioned as lethal mechanism in D + S.

1.2.1. Wax removal

The arthropod epicuticle is mainly made of lipids. The outermost part is a wax layer constituted mostly by hydrocarbons, serving mainly for waterproofing to avoid dehydration [33]. This is a serious threat for small insects and mites, particularly those sessile and exposed individuals. It has been proposed that when arthropods are sprayed with detergent, lipids are removed from the epicuticle, losing its waterproof ability, which in turn causes important water losses and, finally, the death of treated pests [34]. In fact, a significant reduction in both residual epicuticular lipids and body weight (assumed to occur mainly due to water losses) on the obscure mealybug *Pseudococcus viburni* Signoret (Hemiptera: Pseudococcidae) sprayed with detergent solutions was measured ([35], **Table 1**). After the spray, water losses reached up to 3% of body weight 7 h after exposure, and residual waxes were 88–73% below when compared with the control (check) at 24 h. Mortality was positively related with both water losses and wax removal when the agriculture detergent TS 20135 was used, but no significant relationship was found when the surfactants alone (excluding the co-adjuvants from the formulation) were tested.

Santibáñez [35] proposed that mealybug mortality by exposure to detergents might be caused by several mechanisms, including the initial wax removal that might lead to further damage of the integument, but this was not demonstrated. Many reports of pest management with D + S reveal that individuals present a degreased and dehydrated aspect after exposure, suggesting that water losses might be involved in mortality. For instance, the cotton aphid *Aphis gossypii* Glover (Hemiptera: Aphididae) nymphs and adults were strongly dehydrated and their bodies collapsed when evaluated 48 h after the spray with an agricultural detergent [9]. Wax removal (assumed to lead to dehydration) is also evident after exposure to detergents, causing dramatic changes in mealybugs, even a few minutes after the spray ([8, 11], **Figure 1** shows effects on hemipterans either sprayed or immersed in solutions).

Treatments[1]	Detergent (mL a.i.[2]/100 mL)	Water loss[3] (mg)	Residual waxes[4] (mg/mL)
LC_{90}	8.17	1.85 a[5]	14.95 b[5]
LC_{50}	4.45	1.48 b	6.85 b
LC_{10}	0.74	0.89 c	54.76 a
Control	0.00	0.47 c	55.06 a

[1] LC = lethal concentration estimated by Probit analysis; study conducted using a Potter tower, control sprayed with water.
[2] Active ingredient, the sum of surfactants formulated in TS 2035 (see **Table 3**)
[3] Difference between initial (before) and final weight.
[4] Residual waxes extracted with chloroform from 20 P. *viburni* adult females after detergent spray.
[5] Means with different letters in a column are significantly different ($p \leq 0.05$) according to Tukey's test. Data extracted from Santibáñez [35].

Table 1. *Pseudococcus viburni* water losses and residual waxes after detergent sprays.

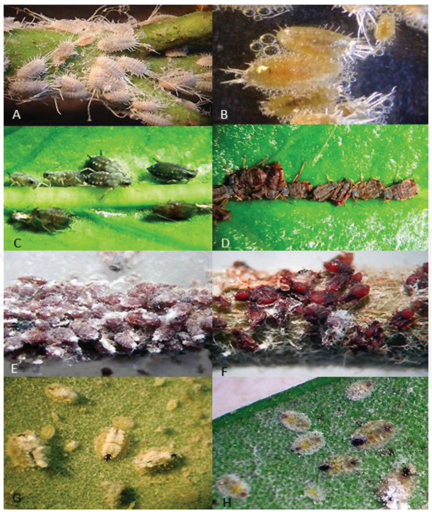

Figure 1. Healthy hemipterans before (left column) and either minutes or a few hours after exposure in 1–2% detergent solutions (right), presenting symptoms of dehydration, browning, body collapse, and wax removal. A, *Pseudococcus longispinus* Targioni and Tozzetti (Pseudococcidae); B, *P. longispinus* after 5-s immersion in SU 120 (see details in **Table 3**); C, *Aphis gossypii* Glover (Aphididae); D, effect of TS 2035 on *A. gossypii*; E, *Eriosoma lanigerum* (Hausmann) (Eriosomatidae); F, effect of TS 2035 on *E. lanigerum;* G, *Siphoninus phillyreae* (Haliday) (Aleyrodidae); H, *S. phillyreae* a few days after sprayed.

Detergents[1] (%, v/v)	**% dislodgment[2] (D)**	**% mortality (M)**	**CD = 100×D/[D + M])**
1.00%	22.2	59.4	27.2
0.50%	21.7	32.6	40.0
0.25%	14.1	17.6%	44.5
Control[3]	3.2	18.8%	14.5

[1] Quix solutions (see **Table 3**).
[2] Individuals found after immersion for 5 s + filtration.
[3] Tap water. Data extracted from Curkovic and Araya [37].

Table 2. *Panonychus citri* dislodgement (D), mortality (M) at 24 h, and contribution of dislodgement (CD) to the control (D + M), after immersion of infested lemon leaves in the laboratory.

1.2.2. Arthropod dislodgement

Detergents and soaps contain surfactants, that is, compounds that reduce the surface tension of solutions, enhancing their capability to wet and wash arthropods off. Thus, sprays can dislodge motile forms of phytophagous pests, as nymphs and adults of mites, thrips, etc. (particularly when the solution runoffs on the leaves). Even not necessarily all removed individuals die, and dislodgement causes significant reductions of populations infesting the foliage. Dislodgement has been highlighted as an anti-herbivore trait [36] that reduces their phytophagous performance on the plant. In a laboratory study, up to 22% dislodgment of the citrus red mite *Panonychus citri* McGregor (Acari:Tetranychidae) infesting lemon (*Citrus* × *limon* (L.) Burm.f.) leaves occurred after immersion in a detergent solution at 1% (v/v), significantly greater than water alone [37]. Mite mortality was also greater along with detergent concentration, but the relative contribution of dislodgment to total control (dislodgment + mortality) was even greater (44.5%) when the lower concentration (0.25%, v/v) was used (**Table 2**). In another study, 22% of the Chilean false red mite *Brevipalpus chilensis* Baker (Acari: Tenuipalpidae) were washed off vine leaves after immersion in a detergent (see **Table 3** for details) solution, but lower concentrations contributed less to total control [38], suggesting that dislodgement depends on the type of detergent and/or the mite species.

Not many reports have demonstrated dislodgment when soaps and detergents are used for pest control, although surfactants have been mentioned as useful tools to wash out arthropods plant substrates (including plant organs) for cleaning produce or pest sampling purposes [39]. For instance, ca. 28% of the western flower thrips, *Frankliniella occidentalis* (Pergande), were removed after the immersion in a 0.1% surfactant solution (see **Table 3**) from infested Coleus shoots (*Lamiaceae*), but the thrips were apparently not harmed [40].

1.2.3. Drowning

Arthropod respiratory system is formed by a net of conducts (traqueae) that allow direct gas exchange with tissues. It is connected to the exterior by spiracles that regulate opening by muscles [33]. The surfactant properties of detergents and soaps allow the solutions to enter the spiracles [41, 42]. The solutions fill the traqueae, causing drowning and death. No reports have been found describing this mechanism for pest control, but several papers have mentioned drowning as a mortality factor after surfactant sprays on insects and mites [43, 44]. In larger insects, this seems to be a lethal mechanism after exposure to D + S [43].

1.2.4. Other mechanisms

Interference with cellular metabolism [41], repellency [30], breakdown of cell membranes [42], abnormal juvenile development [12], caustic activity, uncoupling oxidative phosphorylation, and/or even nervous system disruption [45] have been also indicated as possible modes of action of D + S, but further details have not been found. Interestingly, in nature, surfactants have been highlighted as a mechanism of defense developed by some insects against their predators by producing oral secretions containing surfactants that, for instance, stop ants attacking beet armyworm, *Spodoptera exigua* (Hübner) caterpillars (Lepidoptera: Noctuidae). After exposure, the ants covered by the secretion are engaged in intensive grooming that persisted for a few minutes, enough to save the caterpillar. Besides, after cleaning, ants were reluctant to attack a second time [46]. In fact, the author has regularly poured pure dishwashing detergents (~5 mL on their path) to successfully stop ant columns at home.

1.3. Detergents and soaps used for pest control in agriculture

1.3.1. Formulations

Table 3 presents the characteristics and origin of 16 detergents and soaps used for pest control, or as co-adjuvants, reported in here. Many are liquids that perform better as insecticides and miticides [47], and a few are bars or powders. All were mixed in water to be applied, but bars needed, additionally, chipping and boiling before dilution. Several of the main world producers of cleaning products are represented in the list. About 44% of the products listed in **Table 3** correspond to either dishwashing, housecleaning, or personal cleaning products tested or used as alternatives to conventional pesticides. Thus, most products were not registered for pest control or agriculture use, but the results from research led later, in some cases, to the development of agriculture detergents (e.g., TS 2035 or SU 120 in Chile). Some D + S are produced locally, by relatively small producers, with raw materials easy to obtain, making suppliers and growers, particularly in developing countries, more independent from foreign surfactant producers. Information on D + S formulae was not always readily available and their components were not completely described, indicating only generically the type of compound (no chemical names given) or giving the range of the total surfactant content, but not precise figures. In fact, in many scientific publications reporting on the topic, there are no details on the specific inert ingredients or the surfactants (considered the active ingredients), or their respective proportions [47, 48].

Commercial names and formulations[2]	Companies[3] and countries	Surfactants (a.i.) and %[4] in c.p.	Declared uses[5] and references
Acco Highway Plant Spray Soap, L	Acme Chemical Company, PA, USA	Coconut oil soap[6] (38.5)	ASo, Moore et al. [63]
Break, L	BASF, Chile	Trisiloxane[7] (75)	Co, Sazo et al. [54]
Disolkyn, L	Bramell Ltda., Chile	Sodium disoctyl sulfosuccinate[6] (70)	Su, Sazo et al. [66]
Ivory Clear detergent, L	Proctor and Gamble, OH, USA	Acids salts of coconut oil and tallow[6]	HCD, Sclar et al. [69]
Key soap, B	Unilever, Ghana	Not provided	PCSo, Asiedu et al. [48]
LK dishwashing, P	Biotec S.A., Chile	Not provided	DiD, Arias et al. [47]
M-Pede, L	Mycogen Corp., CA, USA	Potassium salts of fatty acids[6] (49)	ASo, Butler et al. [30]
Nobla, P	Johnson and Diversey, Chile	Sodium alkyl benzene-sulfonate[6] (5-15)	HCD, Curkovic et al. [57]
Palmolive, L	Colgate-Palmolive S.A., Chile	Total fatty acids[6] (71)	PCSo, Arias et al. [47]
Quix, L	Lever S.A., Chile	Sodium benzene-sulfonate[6] (15-30%)	HCD, Curkovic et al. [34]
Safer, L	Agro-Chem, CA, USA	Potassium salts of fatty acids[6] (50)	ASo, Osborne and Petit [65]
SU 120, L	Johnson and Diversey, Chile	Sulfonates (14.9); lauryleter sulpfnate[6] (17.8)	AD, Ripa et al. [55]
Sunlight Dishwashing Detergent, L	Unilever, Ghana	LAS[6] (10-20) + sodium lauryl ether sulfate[6] (5-10)	DiD, Asiedu et al. [48]
Tecsa fruta, L	Protecsa, Chile	Xylene sulfonate[6] + nonylphenol[7] (1.5-2)	AD, Curkovic et al. [38]
Triton X, L	Sigma, MO, USA	Octyl-phenol hydrophobe series Polyethylene glycol ether[7]	ASu, Warnock and Loughner [40]
TS 2035, L	Pace Intl., Chile	15-17% sodium dodecyl sulfate[6], 4-6 ethoxilated alcohol%[7]	AD, Curkovic et al. [9]

[1] Not an exhaustive web search, thus, the characteristics were not found for all products; some of them can have different commercial names elsewhere.
[2] Liquid (L), powder (P) or bars (B).
[3] Fabricant or distributor at the time the original paper was published or current owner of the product.
[4] Either % w/v or v/v of surfactant(s) (considered the active ingredient) reported in the commercial product (c.p.) when available
[5] Reported use, housecleaning (HC), personal cleaning (PC), agriculture (A), horticulture (H), detergent (D), soap (So), or surfactant (Su) used as co-adjuvant (Co) or dishwashing (Di) detergent; bibliographical references where the product was cited
[6] Anionic surfactant.
[7] Non-ionic surfactant.

Table 3. Characteristic[1] and origin of some of the detergents and soaps reported herein.

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1.3.2. Surfactants

The first synthesized surfactants were soaps, molecules with a relatively long hydrocarbon hydrophobic chain in one extreme, capable of binding lipids, and a hydrophilic carboxylic group in the other extreme bonded to either sodium or potassium [49]. Soaps are relatively easy to produce from natural raw materials (animal fat or vegetable oils). They were used in pest control as far back as the eighteenth century [50]. However, soaps did not perform efficiently in hard water (where they precipitate) or at low temperatures. Therefore, and also considering the shortage of raw materials in Europe after World War I, detergents were developed in the 1930s, overcoming the limitations of soaps [20], mainly by substituting the carboxylic end by a sodium sulfate or sulfonate, or other hydrophilic group. The main uses of both types of compounds worldwide are housecleaning (laundry and dishwashing), personal care (body washers, shampoos), but also in agriculture, food processing, etc. Today, the main raw materials used to produce surfactants are petroleum-based materials and plant oils (mainly from soybean and palm). The latter has an increasing production due to, among other factors, its low cost and toxicity, and natural origin. In fact, from the point of view of their use in agriculture, detergents, unlike soaps, cannot be used in organic farms because they are synthetic, nonnatural products. The recent changes in surfactant markets (including the need for safer, environmentally friendly, and economical products) have stimulated the production of new compounds. For instance, food and pharmaceutical processing surfactants or edible surfactants are available, providing alternatives that need to be tested as pesticides, besides older compounds [29, 51]. Surfactants in D + S reported herein are described in **Table 3**. In solution, surfactants tend to adsorb to the surface or interphase of materials, reducing hydrogen bridges between water molecules, thus improving their wetting capabilities. Besides, in contact with water, surfactants form micelles or small spheres, usually having the hydrophobic end inside, binding lipids, and the hydrophilic end outside. In this way, lipids are removed (degreasing effect) from the substrate and get diluted (solubilized). The electric charge of the hydrophilic end in solution can be neutral (non-ionic surfactants), negative (anionic, the most common among the D + S reported herein), positive (cationic), or both (negative and positive) [49]. Ionic surfactants can modify the pH of the solution. For instance, anionic surfactants tend to slightly acidify the pH, but they perform better at basic pH; therefore, the detergent formulae include some buffer agents. In fact, it was found that agriculture detergents (including all co-adjuvants) tend to alkalinize the solution in distilled water (pH: 7.8–8.9, depending on the concentration) [35], but only when above 1% (v/v) was prepared, maintaining the pH neutral otherwise [52]. In many cases, the surfactants vary between D + S formulations (in their chemistry and/or proportions), affecting their insecticide/miticide performance [38, 53]. Therefore, the activity of D + S needs some standardizing procedure in order to compare their activities as pesticides, for instance, comparing the proportion of surfactants (see below the case of some mealybugs), although differences can also be due to the particular type of surfactant, so this issue needs further research. Besides the house or personnel cleaning products, and some agriculture detergents, other sources for pest control are the co-adjuvants commercialized for specific functions, for example, wetting agents when mixed with pesticides or fertilizers in agriculture. Some of them have been individually or in mixtures tested as insecticides and miticides [52, 54].

1.3.3. Efficacy as insecticides or miticides

Most reports of pest control with D + S state relatively high levels of control (measured as either density reduction or mortality) against target pests. Those levels were usually achieved with the highest concentration tested, in most cases under or equal to 2%, either w/v or v/v, and considering the largest number of sprays [31]. The efficacy was directly related to coverage (the volume of water/ha used) and the stage of the pest (younger instars, except eggs, are the more susceptible ones, see **Table 4**) [11, 55]. In a few reports, however, the level of control obtained with soaps was poor [31, 56] or not significant when compared to some standard treatments (a recommended conventional pesticide). Maximum control was frequently measured when evaluations were conducted about a week after application, presumably due to a slower activity on arthropods than conventional pesticides [9], but some rapid stop-feeding response was also reported for insecticidal soaps, although mortality was achieved more slowly [12]. A few formulations include insecticides (e.g., pyrethrins are added in small amounts, [12]) for uses as agriculture soaps or louse shampoos [45], increasing their biocidal activity because of the addition of the natural neurotoxicant, but this is not the case of the products reported herein.

Detergents	**LC_{50} on**	**LC_{90}[3] on**
Tecsa fruta	1.4 b[2] (nymphs)	4.2 (nymphs)
	2.5 a (adults)	9.7 (adults)
SU 120	1.2 c (nymphs)	7.5 (nymphs)
	1.4 b (adults)	n/d[4] (adults)

[1] LC_{50} obtained by Probit analysis of data from commercial products in solutions (%, v/v) applied with a Potter tower (SU 120) or immersed 3 s in a solution (Tecsa fruta), values at 24 h after exposure.
[2] Means with different letters are significantly different based on Curkovic et al. [68].
[3] LC_{90}, values calculated from unpublished data, LC_{90} were 3–6× greater than the LC_{50}.
[4] No data are provided because maximum observed mortality was <50%.

Table 4. LC_{50}[1] and LC_{90} for *Myzus persicae* nymphs and adult females exposed to two agriculture detergent solutions.

1.4. Challenges and opportunities of detergents and soaps for pest control

1.4.1. Phytotoxicity

Toxicity to plants is a risk associated to the use of D + S, particularly at concentrations above 1–2% (v/v), but this effect should be a function of the proportion and type of surfactant(s) in the commercial formulation. It also depends on the plant species (its specific susceptibility or tolerance), their physiological condition, morphology, and growth stage. Phytotoxicity affects mainly leaves, flowers, and fruits [27, 57]; symptoms on the foliage range from yellowing to bronzing, and wilting or curling, up to necrosis and defoliation, whereas in fruits they range from small brown spots or massive epidermal browning to fruit dropping (**Figure 2**). Petal flowers can become brown or even necrotic when D + S are applied during flower bud appearance and blooming. These symptoms are also observed after repeated sprays with high concentrations (usually above 1%) of detergents [58] or when plants are under some type of stress (e.g., shaded plants, see below the case of *E. lanigerum*). It is believed that epicuticle wax removal in plants, at least in part, is responsible for this type of damage [34, 35]. Plant external cuticle is mainly made of cutin (one of two waxy polymers of long-chain fatty acids that are the main components of the plant cuticle, which covers all aerial surfaces of plants), and waxes that offer strong resistance to evaporation from the underlying cells [59]. These compounds can be removed by D + S, depending on the type and concentration [60], significantly increasing evaporation. Water losses can also occur through the stomata that have an opening regulated by guard cells [59] that are affected by some soaps, getting through their membranes [42]. Phytotoxicity has been observed more frequently in plants with pubescent surfaces (leaves), where the droplets act as lens causing burning [12], and lesser in those with heavily waxed leaves, limiting the use of D + S depending on the plant species and leaf anatomy. Regarding the pH of the sprayed solution, we have presented examples of data indicating only small changes not expected to be hazardous for plants when 1% or lower concentrations are used. In **Figure 2** (left picture), a recently set olive fruit (cv. Sevillana) presents browning on the lower half after exposure to an agricultural detergent (**Table 3**, [27]), even at 0.5% c.p. (v/v). The fruit later aborted, and the same happened in several other table (Kalamata, Manzanilla) and olive oil varieties (Arbequina). In fact, because of phytotoxicity, detergents (and horticultural oils) should not be applied to olive trees from flower bud to stone hardening (about 1-cm fruit diameter) [27]. Similar results have been observed in grapes at blossom and fruit set. These examples demonstrate specific susceptibility to surfactant sprays, since D + S can be applied at the same or even greater concentrations, on other fruit species during fruit set, without phytotoxic effects (e.g., apples and citrus). However, **Figure 2** (right picture) presents apple leaves damaged by weekly detergent sprays (n = 4, at 0.5% (v/v), see **Table 5**), probably due to the abnormal susceptibility of plants maintained for a long time (above a year) at a greenhouse covered by a shade mesh, before the trial was conducted. This condition might reduce the thickness of the cuticle layer and make the plant more susceptible to damage (sun burnt) or water losses [61]. In fact, foliage of apple trees in orchards sprayed with the same detergents (at 1%, v/v) did not present phytotoxic symptoms at all. Therefore, it is necessary to test at a small scale detergent and soap sprays, case by case, before being sure to conduct a larger-scale application. To do this, the evaluation should be conducted within a week or less after the spray for symptoms to be observed [27, 31], thus selecting tolerant species or adequate plant growth stages. On the other hand, phytotoxicity caused by D + S can be considered useful in crop protection, since some can be used directly as either herbicides or herbicide co-adjuvants [42].

Figure 2. Symptoms of phytotoxicity on recently set olives during the spring (October, left), and on apple foliage in the middle of the summer (February, right), after a spray with detergents (0.5% or 1%, v/v, respectively).

Treatments	# sprays Dafs[3]	% mortality
TS 2035 0.5%	1 (0)	15.2% e[4]
"	2 (0 and 7)	38.0% de
"	3 0, 7, and 14	62.8% bcd
TS 2035 1.0%	1 (0)	61.1% cd
"	2 (0 and 7)	84.4% abc
"	3 (0, 7, and 14)	90.5% ab
Chlorpyrifos[1]	1 (0)	94.4% a
Control[2]	3 (0, 7, and 14)	0.0% f

[1] Lorsban 75 WG was applied once on February 12, 2014 (= day 0), at 80 g c.p./hL.
[2] Tap water was applied every time.
[3] Total number of sprays during the 2-week period.
[4] Days after first spray (dafs) the successive applications were conducted.
[5] Means with different letters are significantly different (p≤0.05) according to Tukey's test.

Table 5. Mortality of *Eriosoma lanigerum* adults and nymphs infesting potted apple trees, with up to 3 weekly sprays of an agriculture detergent (at two concentrations) versus one spray of chlorpyrifos.

1.4.2. Lack of residual activity

Some reports state that insecticidal soaps are not persistent since they suffer rapid degradation [12]. However, some other studies on detergents or surfactants have demonstrated that their residues persist on the substrate after application. Triton X and Tween 80 (see **Table 3** for details), two surfactants used as co-adjuvants, produced persistent residues, at least a week after the spray on tomato fruits or tobacco leaves, respectively [60, 62]. Despite that, D + S residues do not have residual activity in terms of protection over time [31], which occurs only in solution [45], thus they are considered strictly contact pesticides (spray or topic exposure), some affecting the pest quickly [12]. Some soaps have been incorporated into a diet causing a slight mortality in the laboratory [56], showing some ingestion activity, but only at high concentrations (5× the recommended field rate). There is, however, some "residual" activity shortly after the application of D + S, if the solution lasts as either droplets or a liquid layer on the foliage and contacts the arthropod [47]. There is also the possibility of re-hydration if, for instance, relative humidity increases enough and shortly (after the spray) during fog events, to re-dilute D + S residues. It has been proposed to conduct repeated and frequent sprays of D + S to counteract their lack of residual activity on recurrent pests (see **Tables 5** and **6** for successful examples), but some concerns have been mentioned about the potential buildup of surfactants in the soil [63], although specific studies have not been conducted, except for some co-adjuvants [64]. On the other hand, the lack of residual effect turns out to be an advantage, preventing mortality of beneficial arthropods released after residues, which are dry, making D + S compatible with biological control and IPM programs.

Treatments	# sprays[3]	Dafs[4]	% mortality[5]
TS 20351[1]	1	0	29.0 cde
	2	0 and 10	23.7 de
	3	0, 10, and 20	51.7 abc
	4	0, 10, 20 and 30	54.2 ab
	1	30	49.6 cd
Imidacloprid[2]	1	0	78.8 a
Control	0	0	12.0 e

[1] At 0.5% c.p. (v/v).
[2] Confidor 350 SC applied once on January 24, 2013 (day 0), at 60 cc c.p./hL.
[3] Total number of sprays/treatment.
[4] Days after first spray (dafs) the successive applications were done.
[5] Means with different letters are significantly different ($p \leq 0.05$) according to Tukey's test. Unpublished data.

Table 6. Mortality of *Parthenolecanium corni* nymphs infesting vines, with one to four sprays (every 10 days) of TS 2035 at 0.5% versus one spray of imidacloprid.

1.4.3. Legal restrictions and registration

Authorization is an obligatory requirement to legally utilize D + S as pesticides in agriculture. It implies the demonstration of no toxicological risks (including ecotoxicology) and agronomic efficiency, based on science, excluding compounds that do not comply. The process requires a large effort, and it is slow and expensive, making the agrochemical industry to proceed only when the economic return is attractive. There are a few cases of registered D + S as insecticides and/or miticides for agriculture, a few in the United States [30, 65]. In Chile, there has been one registration (Disolkyn, see **Table 3**) for a few years during the mid-2000s [66], but it was not renewed, so there are no legally available D + S for pest control currently in this country. Despite that, non-registered D + S have been used in Chile for pest control, suggesting that they do not cause problems. Their use with no sanctions has occurred because this is an issue not regulated specifically, since the products can be declared as used, for instance, as tree cleaners (an authorized use in some agricultural detergents), pest control being the real purpose [11]. However, growers subjected to the certification process do not use D + S. This causes a serious bottleneck for registration and development for these compounds as tools for pest management. Besides, the chemical and agrochemical industry have not made large efforts for detergent registration as pesticides, in part for a low market expectative in economic terms (low profit), and also due to the difficulty and elevated costs involved. For D + S, government agencies require the same requisite used for the registration of conventional pesticides, making even more difficult for the industry to spend efforts in a registration process for these types of compounds. However, as mentioned before, many surfactants, detergents, and soaps are safe for the environment and the users, and some are even food additives or edible surfactants, so there is room for pesticide development to identify and select those D + S with very low risks. Similar to the case of horticulture oils, pheromones, or biological pesticides [12, 13, 18], D + S should be developed as safe products, obviously excluding those questioned and dangerous [15, 17]. Therefore, authorization for D + S must be addressed by all the actors involved: government (registration agency, Departments of Health and of Agriculture), producers (the surfactants industry and agrochemical companies, suppliers, and distributors), the academic sector (researchers from the agronomic, chemistry, and toxicology areas), and even grower and consumer organizations (particularly those advocated to consumption of safer foods). Only by acting jointly, the analysis, selection, and development will lead to register and use D + S in pest management. Once available, these compounds will serve in IPM, but also to conventional or organic production schemes, and serve in many complex scenarios (e.g., used very close to harvest with no other management options).

1.4.4. Spray conditions

Since D + S work strictly by direct contact, application should maximize the exposure of the pest as much as possible. Spray equipment must be adapted, for instance, modifying nozzles orientation in order to apply from underneath the leaves or fruits, where mealybugs, spider mites, or whiteflies use to feed [9]. Air-blast or powered backpack sprayers have been preferred for D + S applications, since better coverage and smaller droplets are achieved [9, 27]. If possible, trees might be pruned before spraying surfactants in order to increase pest exposure and air circulation that will help in the dehydration of treated insects and mites [9]. Solutions should be applied considering whole coverage of infested organs, using high volumes of water/ha and high-pump pressure during the spray [8, 63]. Besides, sprays should be done early in the morning or late in the evening to increase the duration of the wet layer and extend their insecticide lifetime [31].

1.4.5. Pest biology and ecology

The habits, biology, and morphology of the pest should also be considered to maximize exposure by D + S sprays. For instance, nocturnal pests (armyworms (Lepidoptera: Noctuidae) or snails (Mollusca: Pulmonata, Helicidae)) should be sprayed at night for direct exposure. In fact, some noctuids have not been controlled efficiently by diurnal soap sprays in the field [56]. For the greenhouse whitefly *Trialeurodes vaporariorum* (Westwood), nocturnal sprays were also recommended, since evaporation is low and adults are less mobile, being more likely reached by the solution [47], but diurnal application is efficient against the sessile stages (older nymphs). In pests known as susceptible to D + S, however, some specific instars are less (or not) vulnerable (e.g., spider mite eggs are less susceptible than mobile forms). In fact, in one report only slight activity against overwintering eggs of the European red mite *P. ulmi* (Koch) was found [67], while significantly greater summer eggs LC_{50} (1.5–2.3×) than adult females of the two-spotted spider mite, *Tetranychus urticae* Koch (both Acari: Tetranychidae), were observed in another study [68]. In the case of whiteflies, eggs and pupae are less susceptible, whereas nymphs or adults are severely affected by detergent sprays [27]. Mealybugs (pseudococcids) are difficult to reach by either contact or systemic insecticides in the field when they colonize fruit cavities, woodcuts, or roots [9]. In general, therefore, it is necessary to find the vulnerability for each pest species to be controlled with D + S.

2. Review of agriculture pests controlled with detergents and soaps

2.1. Hemiptera

Most examples of pest species controlled with D + S belong to this insect Order. They are the main target group because of their (a) size, being small (most), therefore highly dependent on their protective wax layer; (b) exposure on plant tissues, many being relatively easy to reach and/or remove from the foliage by the spray; (c) type of cuticle, being either soft or thin, thus more susceptible to D + S; (d) damage, as most species cause it when reaching high populations, thus, a significant reduction (but maybe not eradication) is enough to secure satisfactory yields, as expected for surfactants; and (e) null development of resistant populations as with conventional insecticides, thus, management with multisite D + S helps to avoid or reverse the problem, etc. The following review presents the most important hemipteran groups controlled with these types of compounds.

2.1.1. Aleyrodidae

Whiteflies are plant-sucking pests, having many generations per crop cycle, which infest mainly the foliage (usually the underside of leaves) of vegetables, tree fruit orchards, and ornamentals. They affect plant growth and yield by sap sucking, transmission of some diseases during feeding, and release of honeydew on the foliage and fruits, allowing the colonization by sooty mold. This fungus reduces both photosynthetic capacity and the value of the produce (downgrading the price of fruits and vegetables). Honeydew also serves as food for attendant ants that disturb biological control agents. Whiteflies have externally a conspicuous white-dusting wax layer to protect them from dehydration, also serving to reduce insecticide exposure. Detergent and soap sprays have been widely used to target the underside of the leaves and control whiteflies, despite some limitations against these pests as the lack of both systemic activity and residual effect. To counteract these narrowing factors, sprays require to be frequent, to cover the whole population. Besides, as whiteflies have several generations lasting about a month per crop cycle, each one should receive sprays. Butler et al. [30] were one of the first researchers in testing 16 D + S (e.g., M-Pede, Palmolive, etc.; see details in **Table 3**) on the control of the sweet-potato whitefly, *Bemisia tabaci* (Gennadius), 48 h after spraying several vegetable and ornamental species under greenhouse conditions. The production of honeydew by nymphs was measured as an evidence of nymph survival. In fact, there was a significant and inverse regression between the number of honeydew droplets (trapped on sensitive paper placed below infested leaves) and D + S concentration. The authors also found above 85% mortality (against the control sprayed with water) with 13 D + S at 1% either v/v or w/v, even under heavy infestation. Besides, adult whiteflies were removed from the leaves by the sprays and some ended adhered to the lower foliage and died. This is an additional control effect when using these types of compounds and it probably explains the reduction in adult's captures in traps after the application. D + S have also been tested on the greenhouse whitefly, *T. vaporariorum* (Westwood), but with dissimilar results. For instance, D + S were sprayed on infested seedling tomatoes (less than 10-leaf stage), and yield, plant toxicity, and nymph reduction were measured. Slight but significant nymph reduction (compared to the control) was observed when M-Pede insecticidal soap was sprayed at 2% (v/v), not causing yield losses. Weekly applications were suggested to control *T. vaporariorum* in tomato greenhouses, without plant toxicity risk [69]. Several other detergents (e.g., Ivory Clear detergent) used at 2% significantly reduced nymph density, but they also caused damage on the plant and yield reduction. In another study evaluating 12 D + S, only one product (LK dishwashing at 4–5% c.p. v/v) provided a bit over 50% adult *T. vaporariorum* mortality 24 h after the spray on infested bean plants (nymph mortality was not evaluated). Solid and liquid soaps caused similar results (below 35% mortality), except for Palmolive, that reached ~42% mortality using a 4% solution, but the lethal effect was dependent on the presence of liquid residues on the foliage [47]. High levels of control of the ash whitefly, *Siphoninus phillyreae* (Haliday), in olive trees sprayed with agriculture detergents (TS 2035 and *Tecsa fruta*) at 1–2% v/v, were reported [58]. Best results were obtained when detergents were applied on younger nymph stages (particularly nymph I) infesting potted plants, easier to cover with the spray. In another study in a pomegranate orchard, it was found that *S. phillyreae* nymphs I–III were easier to control whereas eggs and pupae (nymph IV) were far more difficult to kill with the same concentrations; thus, adults can emerge after the spray, not being a good predictor of whiteflies control [9]. Detergents at 0.5% (v/v) and above used against *S. phillyreae* produced toxic effects in Chilean olive orchards when used between flower bud and recently set fruits, precluding its use between those phenology stages, but pomegranates, on the other hand, were highly tolerant to 1% detergent (see **Table 3**) solution, and did not suffer either fruit or foliage damage. Results from other reports [9, 27] confirm that whiteflies are good targets to be controlled by D + S.

2.1.2. Aphidoidea

Aphids (*Aphididae*) are also very important plant-sucking pests, having impacts similar to whiteflies. Aphids tend to congregate on the buds and leaves, and also have several generations per season, but they tend to infest the foliage, twigs, and flowers during the spring, late in the season (close to harvest). Some cause the leaves to curl, forming refuges, being harder to reach with contact insecticide sprays, although this is easier with D + S due to its surfactant properties. Their bodies have less conspicuous wax layers than whiteflies. Because of that, sprays with contact insecticide target directly the colonies. D + S have been widely used to

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control aphids, with similar considerations as in whiteflies. Puritch [70], one of the oldest reports in recent times, found that soaps and their respective fatty acids (at 0.5% v/v) were active against the balsam woolly aphid, *Adelges piceae* (Ratz.) (*Adelgidae*), in Canada. The soap was more effective than the corresponding fatty acid, but both had neither ovicidal nor residual effect. Moore et al. [63] published one of the first reports of housecleaning products (D + S) used against three Aphididae species (the green peach aphid, *Myzus persicae* Sulzer; the spirea aphid, *A. spiraecola* [=*citricola*] (Patch), and the black bean aphid, *A. fabae* Scopoli), infesting several species of ornamentals. They found that Ivory liquid dishwashing at 1–2% (v/v) sprayed until runoff notably reduced populations immediately after the application. Plant toxicity was observed, particularly on plants with pubescent epidermis. In another report [69], the activity of two detergents on *M. persicae* nymphs and adults was evaluated by spraying (SU 120) or immersion (Tecsa fruta), in the laboratory. The last detergent was significantly more active (having a smaller LC_{50}, considering the smaller amount of active ingredients, that is, surfactants in the formulation) regardless of the aphid instar. Nymphs were more susceptible (**Table 4**: LC_{50} for adults was 1.2–1.8× greater).

Woolly aphids (*Eriosomatidae*) are also sucking pests that debilitate the host plant, release honeydew, and cause cankers. *Eriosoma lanigerum* infests roots but also the axils of leaves, twigs, branches presenting cuts, and occasionally the fruits. They produce large amounts of wax filaments, forming a woolly layer that serves as refugee for adults and nymphs, and protect them from sprays. They have up to 11 generations/season, and control is necessary when populations increase, mainly starting at the end of the spring up to harvest, and require repeated applications. Some unpublished data from a factorial experiment conducted on potted-infested apple trees in Chile demonstrated that both factors, detergent concentration and the number of sprays (one and up to three were contrasted in a 2-week period), were significant on *E. lanigerum* mortality, although no significant interaction was found. When comparing with the standard, results suggest the double spray of the 1% detergent solution (TS 2035, see **Table 3**) was as efficient as one application of chlorpyrifos, a residual insecticide (**Table 5**). Besides, three sprays at 0.5% achieved similar results as one or two sprays of the 1% solution, and these concentrations are alternatives if the greatest concentration causes plant toxicity. In fact, apple leaves were damaged by the treatments, probably due to the shade conditions in the greenhouse where the plants were grown, as mentioned before. Overall, woolly aphids were well controlled by the detergent.

2.1.3. Coccidae

Coccids or "soft scales" are important plant-sucking pests that infest mainly leaves and branches, and occasionally fruits, affecting plants similarly than whiteflies and aphids. Scales are relatively exposed to sprays, but their bodies are protected by a thick and hard shield. Because of that, sprays with contact insecticide target mainly young nymphs that have a poorly developed shield. Since coccids have usually one or two generations/year, the timing for insecticide contact sprays must be precisely defined by monitoring. Detergents and soaps have been informed to control coccid pests since several decades ago (e.g., Singh and Rao, 1979, on the green scale, *Coccus viridis* (Green) [71] in India), despite their lack of both systemic activity and residual effect. Reimer and Beardsley [72] found that an insecticide soap spray at 0.8% v/v caused significant reduction of *C. viridis* (~50% less scale survival compared to the control) infesting coffee trees (*Coffea arabica* L.) in the United States, 4 weeks after the spray. However, populations were significantly greater than those achieved with the standard treatment (fluvalinate had almost no scales at the same time), although no details on the scale population composition were provided. More detailed reports informed over 87% mortality (death individuals over the total) on the nymphal stages I and II of the black olive scale, *Saissetia oleae* (Olivier) infesting *Citrus* × *paradisi* (Macfad.) (grapefruit) and *Nerium oleander* L. (oleander), after the immersion of foliage recently colonized in two different housecleaning detergent solutions at 0.5–1% (either w/v or v/v, depending on formulations; Quix or Nobla, see **Table 3**) [34, 57]. However, similar mortality on adult females was obtained only with greater concentrations that caused plant toxic effects; defoliation and leaf necrosis was observed when above 2% was used [34]. In Brazil, nymphs and adult females of the pyriform scale, *Protopulvinaria pyriformis* (Cockerell), have also been controlled (over 77% mortality) by spraying a neutral detergent at 2% v/v, without causing toxicity on the dwarf umbrella tree, *Schefflera arboricola* (Hayata) Merr. [73]. More recently, satisfactory control of *S. oleae* young nymphs on commercial olive orchards sprayed with agriculture detergents at 0.5–1% v/v has been reported, but avoiding sprays during plant stages susceptible to toxicity (see above) [27]. The repeated use of detergents (two or more consecutive applications) has achieved a reduction in sooty mold and honeydew production (reducing the presence of attendant ants, thus improving conditions for biological control agents), and improved control of recurrent soft scales, somehow replacing detergents lack of residual effect [27]. For instance, a field trial conducted during the summer on a Chilean vineyard heavily infested with the European fruit Lecanium scale, *Parthenolecanium corni* Bouché, mainly targeting the first nymph instar of the second generation, obtained up to 54% mortality after up to four sprays (applied every 10 days) (details in **Table 6**). Results indicate that mortality increased significantly over time along with the number of applications, and no toxic effects on plants were detected even after four successive sprays at this concentration (0.5%). Interestingly, a single spray of detergent applied at day 30 provided 49% mortality (significantly similar to the three-spray treatment), but allowed the nymph population to develop and cause damage for over a month. These results suggest that a similar program of sprays, but at 1% (considered still safe for vines), might significantly improve control of this scale in vineyards. Besides, this program of repeated applications would also serve to control important and synchronic pest as aphids, mealybugs, thrips, and spider mites, all susceptible to soaps and detergents.

It is worth noting that other coccid species have been reported to be satisfactorily controlled by D + S: the soft scale *Ceroplastes* spp., Sabine, 1969 in Australia [74], the oldest report on the use of surfactants alone as insecticide during recent times; the pine tortoise scale, *Toumeyella parvicornis* (Cockerell), in the United States [75], whereas a few scales species have not been controlled, for example, a spray of an insecticidal soap on the calico scale, *Eulecanium cerasorum* (Cockerell), an invasive pest of shade trees in the United States, was rated as relatively ineffective [76]. Overall, these results indicate that coccids are good targets for D + S, but the responses vary between species and that they depend on the management strategy.

2.1.4. *Diaspididae*

Armored scales are also sucking pests, but have a dorsal and protective shield not glued to the body. They colonize mainly branches and fruits (and eventually the leaves) of tree fruit orchards and ornamentals, but do not produce honeydew. Only nymphs I are mobile (crawlers), but once they set on a structure, they lose their legs and become sessile. Diaspidids have usually two to four generations/year. Reports on armored scale control with D + S are less frequent. For instance, the mortality of the oleander scale *Aspidiotus nerii* Bouché nymphs recently set in the wood, 1 week after application on a Chilean olive orchard, reached 60–70% with two agriculture detergents (an horticulture oil reached less than 40%), whereas chlorpyrifos provided close to 100% mortality ([58], **Figure 3**). However, the level of mortality with the detergent spray declined dramatically the next weeks because of the lack of residual effect, whereas mortality with chlorpyrifos kept almost unchanged 5 weeks later due to its long residual effect. The control of the white mango scale, *Aulacaspis tubercularis* Newstead, with housecleaning detergents was evaluated on mangoes (*Mangifera Indica* L.) in Mexico, achieving significantly less colonies and scales on the leaves in comparison with the control, 1 week after the spray. However, the population density increased rapidly 2–3 weeks after application (due to the lack of residual effect), being greater than those obtained with conventional insecticides [77]. The effect of six housecleaning soaps (details in reference) sprayed on the cycad aulacaspis scale, *A. yasumatsui* Takagi, infesting cica crops (Cycadaceae) in Costa Rica, caused significantly smaller densities of crawlers and significantly greater numbers of dead females after the application of soaps (~3%, v/v) with a backpack sprayer [78]. However, the spray of some detergents significantly reduced the activity of entomopathogenic fungi (*Metarhizium*) as well. These results also suggest that surfactants might act as contact fungicides against some plant fungal disease agents.

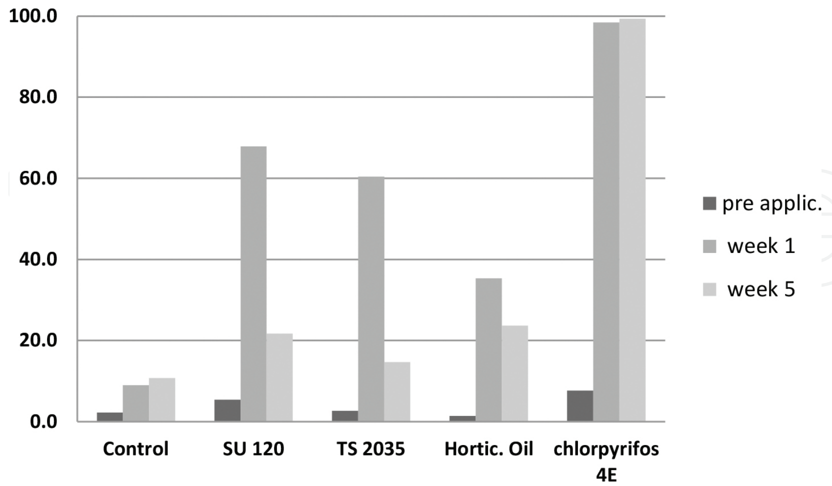

Figure 3. Mortality (%) of *Aspidiotus nerii* nymphs I (about 1000 individuals were counted per treatment/date) infesting olives sprayed with 10 L of detergent solution/tree, with two products (SU 120 and TS 2035, both at 1%, v/v), a horticulture oil (1%, v/v), and chlorpyrifos (at the recommended rate: 120 mL c.p./hL). Evaluations were conducted right before (pre-application: natural mortality was <10%) and 1 and 5 weeks after application, Copiapó, Chile. Data extracted from Curkovic and Ballesteros [58].

2.1.5. Pseudococcidae

Mealybugs are, in general, similar to soft scales regarding the effect on infested plants. However, mealybugs do not significantly reduce plant growth and tend to infest fruits and branches instead of leaves, wood crevices and cuts, zones of fruit contact and calyx cavities, where they can stay even after harvest. Some are serious quarantine problems for exports. Because of that, detergents or soaps are usually not used for mealybug control in orchards oriented to export (however, see the use as postharvest treatment below). Consequently, an intense chemical control program is applied in Chilean orchards exporting fresh fruit, using conventional insecticides (preferring systemic and/or residual products), but their efficacy is still relatively low. This is due mainly to the insect's habits (see Section "Pest biology and ecology"), its phenology (having three to four generations/season they infest the plant the entire season), and morphology (mealybugs are superficially covered and protected by a layer of waxes and woolly filaments). When exposed to sprays, however, mealybugs are highly susceptible to contact insecticides, including D + S. For instance, two agriculture detergents, Tecsa fruta and SU 120, were compared to control *P. longispinus* under laboratory conditions, finding significantly lower LC_{50} values (~1.9%, v/v) in the latter commercial product versus ~18% (v/v) in Tecsa fruta, which contains almost 8× less, and different surfactants. Besides, this study also showed that younger individuals (nymphs II) were significantly more susceptible than adult females and mortality was greater when more coverage (spray volume) was used. Interestingly, at greater concentrations and spraying volumes, mealybugs were glued to the surface by waxes removed from the cuticle and deposited under their bodies [8]. In a more recent study, a significant reduction (82.4% in a 2-year average from the control) in mealybug densities (the cotton mealybug, *Phenococcus solenopsis* Tinsley, and the papaya mealybug, *Paracoccus marginatus* Williams and Granara de Willink) per cotton plant (*Gossypium hirsutum* L.) after a 0.1% (w/v) powder detergent solution (no data on name or composition provided) was obtained after spraying eight times during two seasons in India. The detergent was overcome only by acephate and chlorpyrifos treatments, which reached above 95% reduction, but the detergent provided better control than several entomopathogens (*Beauveria, Metharizium*) and neem oil (ranging from 23 to 69% reduction), and was more selective to ladybirds (Coccinellidae) and spiders [79]. In another two reports, a significant control of the citrus mealybug, Planococcus citri (Risso) was found, by soaps [80], or by D + S on white yam (*Dioscorea cayennensis* subsp. *rotundata* (Poir.) J. Miége) 14 days after being sprayed with a detergent (sunlight at ~1.9% c.p.) and a soap (key soap at ~2.5% (w/v) c.p.). Mortality of *P. citri* on stored white yam was above 92% whereas soybean oil reached 99%, and cypermethrin and imidacloprid provided total control. The authors concluded that all detergent, soap, and soybean oil treatments are alternatives that need further research as postharvest treatments [48]. In a few reports, mealybug control with detergents and soaps has not been successful, in part attributable to the formulation tested, probably under ongoing efforts for development, but all articles emphasize the need to continue the research to identify conditions to obtain better control [81]. There are reports of species belonging to other hemipteran families controlled with D + S: *Capulinia* sp. (*Eriococcidae*) [82] in Venezuela, and the mobile scale of the olive tree, *Praelongorthezia olivicola* (Beingolea) (*Ortheziidae*) [83] in Chile, somehow confirming Hemiptera as the main target group for these types of products.

2.2. Thysanoptera

Thrips are serious pests of vegetables, flowers, and fruit orchards, mainly affecting cut flowers and the skin of fruits (causing russet). They can produce silvering on flowers, leaves, and fruits, downgrading their value. Adults and nymphs are not sessile but tend to stay inside flower structures, under sepals, or at the contact point between either fruits or leaves and fruits. Therefore, D + S can be useful resources to reach them at those protected sites, by being used alone or as co-adjuvants (as surfactants) for conventional insecticides. However, trials evaluating thrips control have achieved different results in terms of mortality or density reduction when D + S have been used alone. For instance, the use of an agricultural soap (Acco Highway plant spray soap at 1% v/v) on the greenhouse thrips, *Heliothrips haemorrhoidalis* (Bouche) (Thripidae), caused important reductions on populations on infested ornamental plants (*Acacia longifolia* (Andrews) Willd; *Pittosporum tobira* (Thunb.) W.T. Aiton) after every spray (n = 4 in a 3-week period), but not after only one spray [63]. On the other hand, almost negligible mortality on the Western flower thrips, *Frankliniella occidentalis* (Pergande) (Thripidae) has been reported after exposed to a soap solution (Soapline containing 60% potasic soap, Syngenta Agro, Spain) by either a residual (treated leaves were sprayed before exposure, so no control should be expected) or a topical bioassay [84]. In the latter case, results were assumed to be due to a low efficacy of the soap used, but it might also be due to the short exposure time. These results suggest again the possibility of differential responses to D + S in distinct species from the same insect family.

2.3. Acari

Spider mites feed mainly on the content of epidermal and parenchymal plant cells. While feeding, they do not reach vascular vessels; therefore, they do not produce honeydew. However, high populations can quickly develop on leaves causing bronzing, necrosis, and defoliation due to cell damage and the release of toxic substances. Mites tend to colonize the underside of leaves, where they need to be sprayed with contact and residual miticides, since colonization (for instance, from overwintering sites to the foliage developing during the spring) can last several weeks. During their development, they have sessile phases (proto- and deuto-nymphs), otherwise they are considered mobile arachnids. Besides, spider mites have several generations a year, being necessary to repeatedly control them along the season when populations reach dangerous densities. Some of the first modern reports of D + S used to control agricultural pests are related to spider mites [63, 65].

2.3.1. Tetranychidae

Osborne and Petit [65] found that the lowest insecticidal soap concentration (Safer at 1.25%, v/v) was effective in controlling adults and eggs of *T. urticae,* but also killed adults of the predatory mite *Phytoseiulus persimilis* Athias-Henriot (Phytoseiidae), although not their eggs. Therefore, predators can be used in conjunction with applications of low concentrations of soaps, giving better control than either tactic alone, provided that the release of the biological control agents is conducted after the spray. More recently, a significant effect of the agricultural detergent Disolkyn (at 0.1 and 0.15%, v/v) on *P. ulmi* (including some ovicidal effect) was found on severely infesting apple (*Malus domestica* Borkh.) trees in Chile, with a lesser effect onto the predatory mite *Neoseiulus californicus* (McGregor) (Phytoseiidae) (*N. californicus* had a good population recovery after the spray) in comparison with the standard treatment having residual effect (Pyridaben) [66]. In another study, the detergents SU 120 and Tecsa fruta were evaluated on mortality of *T. urticae* eggs and adult females, set on double-sided tapes placed on a slide immersed in detergent solutions in the laboratory [68]. The former product was significantly more active killing mites (smaller LC_{50}) for both instars. Eggs were significantly less susceptible than adults to both detergents. In another study, TS 2035 and M-Pede (**Table 3**, [9]) were sprayed at 1% (v/v) on a population of *Oligonychus* sp. mobile forms severely infesting a pomegranate orchard (**Table 7**). Both surfactants were statistically as efficient as the standard treatment (Pyridaben). Evaluations 2 and 9 days after the spray showed that populations did not recover in D + S treatments, whereas they were significantly greater in the control, causing subsequent damage on the foliage and fruits. No significant plant toxicity was observed. A horticulture oil also performed satisfactorily, but it had a slightly greater recovery of the mite population by day 9 [9].

Treatments[1]	**Days after a spray**		
	0	2	9
M-Pede	60.0 a[3]	17.5 ab	20.8 b
TS 2035	54.8 a	11.5 ab	9.3 b
Horticulture oil	56.0 a	12.0 ab	33.8 ab
Pyridaben[2]	53.3 a	1.8 b	6.5 b
Control	127.3 a	138.3 a	199.3 a

[1] Surfactants and oil (Ultraspray) at 1% c.p. (v/v).
[2] Sanmite 20 WP applied at 75 g c.p./hL.
[3] Means with different letters within a column are significantly different ($p \leq 0.05$) according to Tukey's test. Extracted from Curkovic et al. [9].

Table 7. Densities of *Oligonychus* sp. mobile forms on pomegranate before (day 0 = April 11, 2013) and after a spray (days 2 and 9) with several miticides.

2.3.2. Tenuipalpidae

A recent report indicates that the detergent SU 120 at 1.5% (v/v) sprayed in an infested vineyard had a significant effect on reducing *B. chilensis* mobile stages, particularly during the summer. Density reduction was not significantly different from the standard miticide acrinathrin. Mite recovery was observed almost 1 month after the spray, but eggs were apparently less affected [38].

2.4. Detergents and soaps used against other organisms

Other insects than those addressed herein, as armyworms (Lepidoptera: Noctuidae, [56]), cockroaches (Blattodea: Blatellidae [43]), and ants (Hymenoptera: Formicidae [44]) have been reported as controlled by D + S, or at least affected. Besides, the control of other organisms including mollusks [85] and fungi [86] with D + S or surfactants has also been reported. All this evidence demonstrates that the potential target for this type of control tactic is far beyond sessile, soft integument, and small insects or spider mites.

3. Costs and economic benefits of using D + S

Costs of detergents or soaps used against agricultural pests, in general, should be relatively low per spray (and it will become even lower if D + S increase their use in agriculture), but there are some exceptions (e.g., expensive insecticidal soaps sold in smaller containers for garden pests in the United States). **Table 8** compares the direct costs of applying a detergent program versus a conventional insecticide, considering having a residual effect shorter or similar to the period of evaluation in the field, and conditions where both strategies have achieved statistically similar levels of control for two pests in either apples or vines (see **Tables 5** and **6**). When comparing the detergent program versus chlorpyrifos used against the apple woolly aphid, the TS 2035 program cannot outcompete the conventional insecticide, being more than 2× more expensive. If Lorsban 4E be used (another much inexpensive chlorpyrifos formulation recommended at 120 mL/hL, with a cost of US$9.7/L), the cost of the detergent program would be about 3× more expensive. However, if other insecticides as buprofezin (Applaud 25 WP used at 120 g p.c./hL, US$42.1/kg) or imidacloprid (Confidor 350 SC) are used (modern and less restricted insecticides, but also more expensive products), considering application conditions and assumptions as described for chlorpyrifos, the standard strategy/detergent program ratio would increase, to near 0.79 (the detergent program being now only 20% more expensive than Applaud) and 1.49, respectively. In the latter case, the detergent program was 49% cheaper (including costs of products, equipment, and workers) than the conventional neonicotinoid. Now, when comparing the use of a neonicotinoid in vines against scales versus the detergent program, results also become very competitive in favor of the detergent strategy (ratio = 1.63). Even considering increasing the detergent concentration to 1% (see discussion in **Table 6**), the detergent program (three sprays) would be 1% less expensive than the use of imidacloprid once. Thus, detergents tend to be competitive when new, more expensive molecules, are used as standard treatments, a trend expected in the next years. The two main factors increasing costs of detergent treatments have been (1) the need to re-apply in order to counteract the lack of residual effect to achieve a level of control similar to that of conventional (and residual) pesticides. Thus, the cost rises due to the increasing value of motorized equipment and drivers, used two to three times (against just one application of the standard); (2) the use of concentrations about 8× greater than conventional pesticides to obtain similar results (detergents need to be used at 0.5–1% c.p. vs. the standards used at 0.06% (imidacloprid) or 0.12% (v/v chlorpyrifos or w/v buprofezin). Besides, since D + S must be applied using high volumes at relatively high concentrations, the amount of product used is larger. The examples presented are based on particular conditions (see the **Table 8** legend). However, the costs should vary among different countries, crops, management strategies, pesticide values, or pest species.

Pest species and crops	#[1] of detergent sprays ≈ to standard[2] control	A: US$ cost of standard (appl./ha)[3]	B: US$ cost of detergent (appl./ha)[4]	Ratio A/B[5]
Parthenolecanium corni on vines	3	113.5	23.2	1.63
Eriosoma lanigerum on apples	2	74.4	77.0	0.48

[1] Minimal number of detergent sprays necessary to achieve mortality not significantly different from the standard treatment (see details in **Tables 5** and **6**).
[2] Standard treatments; one application with imidacloprid (vines) or chlorpyrifos (apples) provided the best control during the period of evaluation.
[3] Cost of application + insecticide in Chile; considering 1 h of equipment (tractor + air-blast sprayer owned by the grower + the driver salary) to cover 1 ha (US$20 for apples or US$8.9 for vines, figures provided by growers); cost of insecticide product for either Confidor 350 SC used at 60 mL p.c./hL in vines (US$174.3/L), or Lorsban 75 WG used at 80 g p.c./hL in apples (US$34/kg), as standard treatments, prices provided by local suppliers.
[4] Cost of application of detergent TS 2035 (US$2.85/L), at 0.5% (v/v) for vines (coverage of 1000 L/ha), or at 1% (v/v) for apples (2000 L/ha).
[5] Ratio between the cost of the standard treatment/detergent program; when greater than 1, the detergent strategy is proportionally more convenient.

Table 8. Comparison of costs (US$) for detergent programs versus conventional insecticides, both as efficiently used to control *Parthenolecanium corni* in vineyards and *Eriosoma lanigerum* in apple trees.

It is important to point out that the exercise above does not consider other benefits of using D + S (used instead of conventional pesticides), as the avoidance of both pest resistance development to chemical pesticides or pest resurgence, or the relative improvement of the environment and the agro-ecosystem, or the reduction of risks of human intoxications (workers and consumers), and so on, because their costs are difficult to estimate. Therefore, if all those costs were valuable, it would probably make the figures much more favorable for D + S. Additionally, the access to markets preferring food not treated with conventional pesticides might also be considered an economic benefit. For instance, IPM or organic products can eventually achieve higher prices than conventional agriculture produce. Besides, foods treated with soaps or detergents will not have major restrictions to reach many different countries since they do not present questionable residues, making easier (and cheaper) the marketing process. In favor of conventional pesticides, an additional economic benefit of their use is their wider spectrum of action against some pest complexes in some crops, but D + S have also demonstrated an extended range of action on pests. Besides, some conventional products can protect for long periods against pests. However, some cannot be used during some phenological stages (Lorsban 4E is used today mainly as postharvest or winter treatment).

Among other examples in the literature, an IPM program was cost-effective at most of the studied sites where the majority of pest were controlled using spot sprays of insecticidal soap or horticultural oil versus the management with conventional pesticides applied on the whole plantation [87]. Another report showed that up to five detergent sprays could be applied before reaching the cost equivalent of controlling pests with conventional pesticides applied twice (only considering the value of the commercial product, but no other application costs) [11]. Similarly, a recommended mixture of a miticide plus the synergic surfactant co-adjuvant Silwet 77 was over 5× more expensive than the cost of using the surfactant alone, which provided most of the control. Unfortunately, the surfactant was not registered as miticide, and was not allowed as a legally authorized control method [53]. Reduced pest control costs, by the use of soaps, were also mentioned by Lee et al (2006) [88].

4. Detergents as insecticide co-adjuvants

The use of surfactants, including D + S, as adjuvant, improves both the active ingredient solubility in the formulation and its physical and biocidal performance (e.g., wetting properties on plant or insect cuticle). Co-adjuvants are added directly to the tank before applications with the same purposes [11]. The oldest report of using soaps (as co-adjuvant) in mixture with other pesticides in the tank was published in Australia in 1969 [74], as a part of the phytosanitary program in Citrus, providing a satisfactory degree of both, coccids and diaspidids control. Later, surfactants were described as co-adjuvants, particularly for cuticle penetration in insects [89]. Last year, an entomopathogen spore suspension (*Metarhizium anisopliae* strain M984) was tested, at the same concentration with or without the addition at the tank of an agricultural detergent (TS 2035; at a nonlethal concentration for *P. viburni* = 0.001%, v/v). A significantly increased mortality of *P. viburni* after the spray was obtained with the mixture (*M. anisopliae* + detergent), whereas the insecticide alone (not mixed with the detergent) provided significantly lower mortality (greater transformed LC_{50}, see **Table 9** [52]). Results show about one order of magnitude of differences in favor of the mixture of spore suspension with the detergent. These results justify the addition of detergents or surfactants during the formulation of commercial products, but they also open chances to reduce rates of pesticides used in the field when D + S are added to the solution in the tank. However, this hypothesis needs to be further tested.

Treatments[1]	**Time (h)**[3]	**LC_{50}**[4]
M. anisopliae + TS-2035[2]	24	8.8×10^6 ab[5]
M. anisopliae	24	8.6×10^7 c
M. anisopliae + TS-2035	72	7.8×10^6 a
M. anisopliae	72	3.3×10^7 c
M. anisopliae + TS-2035	144	6.1×10^6 a
M. anisopliae	144	3.0×10^7 bc

[1] Suspensions (2 mL) of *M. anisopliae* were sprayed/replicate (*n* = 4)/treatment (15–20 P. viburni adult females/replicate), using a Potter tower ST-4.
[2] TS 2035 at 0.001% (v/v).
[3] Three evaluation times were considered given the relatively slow activity reported for *M. anisopliae* on mealybugs.
[4] LC_{50}values were transformed to the respective amount of *M. anisopliae* CFU/mL.
[5] Means with different letters are significantly different ($p \leq 0.05$) according to Tukey's test. Extracted from Villar [52].

Table 9. *Pseudococcus viburni* LC_{50} values of a *Metarhizium anisopliae* strain M984, with or without the addition of TS-2035 at 0.001% (v/v) at different times after spray.

5. Postharvest control of pests with detergents

Immersion of the fruit in warm water has been used as postharvest pest control against several pests on diverse fruit species [90, 91]. Besides, several D + S are allowed for postharvest uses, including fruit cleaning. The combination of both approaches (warm detergent solution) was tested, finding that pomegranates infested with mealybugs and immersed in a 1% (v/v) TS 2035 solution (at 47°C) for 15 min, maintaining the pH at either 5.5 and 8.5, notably (but not totally) controlled *P. viburni*, a pest with quarantine status, usually found in the calyx cavity in postharvest (**Table 10** [92]). There were no adverse effects of the treatments on fruit quality; therefore, further evaluation of these factors at greater levels should be conducted to obtain total control, eventually becoming in an alternative to fumigation.

Temp.[1] (°C)	Det. Conc.[2]	pH[3]	Exposure time (min)[4]	Adult females	Nymphs II and III	Nymphs I	All mealybug stages
15 ± 2	0	5.5	15	2.75[5]	8.50	8.75	20.00
15 ± 2	0	8.5	15	2.00	6.25	22.00	30.25
15 ± 2	1	5.5	15	3.50	3.25	11.00	17.75
15 ± 2	1	8.5	15	2.25	7.75	18.00	28.00
47 ± 2	0	5.5	15	1.25	7.50	9.50	18.25
47 ± 2	0	8.5	15	6.00	4.75	15.25	26.00
47 ± 2	1	5.5	15	0.50	0.25	12.75	13.50
47 ± 2	1	8.5	15	1.00	1.25	2.75	5.00

[1] Water temperature.
[2] % TS 2035 c.p., v/v.
[3] pH corrected from neutral to acid (by adding phosphoric acid) or basic (by adding sodium hydroxide).
[4] Time pomegranates were immersed in solution (minutes).
[5] Means of selected treatments, showing greatest contrasts. Extracted from Carpio [92].

Table 10. Survivals of *Pseudococcus viburni* mobile stages (adult females, nymphs, and total), after postharvest immersion in detergent solutions, plus 1-month cold storage at 5°C, followed by 24 h at room temperature.

6. Conclusions and prospects

Many different agriculture pests (mainly hemipterans and spider mites) are efficiently controlled by detergents and soaps, provided they are directly covered by the spray. The knowledge of their biology and ecology must be used to improve their performance by increasing the pest exposure. The research on new potential targets and the combination of D + S with biological control agents should be studied. D + S can be used as well to avoid or even reverse pest resistance problems.

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The modes of action of D + S as insecticides and/or miticides seem to be mainly wax removal, arthropod dislodgement, and drowning, but it is an unsolved issue in many situations yet. It is then necessary to keep researching on this issue to optimize the use of surfactants as pesticides.

Despite some environmental and toxicological concerns, the appropriate use of D + S, and the selection and formulation of surfactants with minimum risks (for instance, among the offer of new, safe, and low-cost surfactants), makes them potentially useful pesticides, but it is necessary to confirm their relatively safety (for mammals and the environment) and capacity for pest control, in food products.

There is a need to standardize the biocidal activity when comparing D + S, maybe based on the proportion of surfactants in the formulae or contrasting with some standard compound.

Detergents and soaps can be used as co-adjuvants (in the tank) for conventional or biological pesticides. D + S can also be applied first to debilitate pest insects and mites, spraying later insecticides and miticides. In both cases, a rate reduction for conventional (and more expensive and restricted products) is possible, but these issues need further research.

Detergents and soaps can be used in orchards, vegetables, or greenhouses, serving to conventional, IPM, or organic growers, making possible to reach highly selective markets and consumers willing to pay for foods free of insecticide residues and, at the same time, take advantage of their relative sustainable status, replacing conventional pesticides. D + S could be applied very close to harvest, when conventional pesticides cannot, due to the insufficient preharvest intervals.

However, in order to provide satisfactory control and become a greater tool for pest control, D + S need to solve the (a) lack of residual effect, (b) potential for plant toxicity, (c) legal status, and (d) cost. For multivoltine pests, or those infesting crops for long periods, their repeated use over relatively short periods has probed in several cases to provide a control equivalent to conventional (and residual) insecticides. Plant toxicity has been diminished by selecting tolerant crops, or tolerant phenology stages of the crops, excluding otherwise the use of D + S. This issue needs more research to identify tolerant crops and the conditions and mechanism causing plant toxicity, in order to develop safer D + S. The repeated applications of small concentrations of D + S have overcome these two problems, becoming useful tools for IPM productive schemes, particularly considering their multi-site action, selectivity to beneficial organisms, lack of residual effect, and relatively low environment and human toxicity. The facts that D + S are relatively quick to control, easy to produce and use, versatile, and lack major legal restrictions just improve their possibilities to be incorporated in pest programs.

The cost of efficient programs of control with D + S can be competitive with conventional pesticides, depending on the crop, pest, type of grower, and alternatives of pesticides, and it deserves a more detailed analysis, including the precise valorization of several benefits associated to the use of D + S, although some of them are difficult to measure, as lower probability of inducing insecticide resistance or pest resurgence, lower risks of intoxications to workers, etc.

Besides the cost issue, the authorization of D + S as pesticide products seems to be the next main challenge, being necessary that the industry (producers and suppliers), government agencies (regulatory apparatus), scientists (agronomists, entomologists, chemists, toxicologists), and even growers and consumers interact in order to develop a regulation process that allows to increase D + S registrations, particularly those safer compounds, that can be efficiently used with minimum risk (by far lower than conventional pesticides) at pre- and postharvest, becoming valuable tools for sustainable pest management.

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