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Review

A Review of Crop Protection Methods against the Twospotted Spider Mite—*Tetranychus urticae* Koch (Acari: Tetranychidae)—With Special Reference to Alternative Methods

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Abstract: *Tetranychus urticae* is one of the most important pests of many species of economically important crops, cultivated both under cover and in open ground. Feeding *T. urticae* reduces the size and quality of the yield. Nowadays, in connection with the popularization of organic farming and the green order policy, non-chemical methods that provide an effective reduction in the harmfulness of this spider mite are sought. The aim of the study is to present the current state of knowledge on methods of reducing the undesirable effects of *T. urticae* feeding. The paper discusses the main directions of searching for biopesticides against *T. urticae* and provides a list of natural components on which commercially available products are based. The aspect of using the natural properties of plants, micro- and macro-organisms is presented. The paper also deals with the issue of the spread of spider mites in connection with the observed climate changes.

Keywords: secondary metabolites; natural enemies; acaricides; predators; natural plant extracts; entomopathogenic fungi; spider mites

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1. Introduction

The twospotted spider mite—*Tetranychus urticae* Koch, 1836—is a member of the family Tetranychidae, which includes about 4000 species [1,2]. It has been found in all climate zones in Europe, Asia, and North and South America [3–5]. *T. urticae* was originally described based on European specimens. It is regarded as a native species of the temperate climate zone but is also found in subtropical regions. It occurs throughout the United States in greenhouses, where it winters outside its natural range of distribution. Tuttle and Baker [6] reported that this species colonizes deciduous fruit trees in the northern regions of the US and Europe. The host range of *T. urticae* covers about 1275 plant species from 70 genera representing several dozen botanical families [7], either wild or cultivated, including vegetables, ornamental plants, crops, fruit trees and shrubs [2].

The control of *T. urticae* relies mainly on the use of synthetic acaricides, which is not always effective as this species has a high ability to develop resistant populations [2,8,9], and many acaricides have a non-selective effect on predatory mites [10]. The misuse of chemical products for the control of spider mites can cause contamination of the natural environment and food, especially fruit and vegetables meant to be consumed when freshly harvested [11,12]. Acaricides belong to several main groups of chemical compounds: organophosphates, pyrethroids, carbazinates, quinolines, carbamates, tetrazines, diphenyl oxazolines, quinazolines, phenoxypyrazoles, thiazolidines, macrocyclic lactones, pyridazones, and pyrazole derivatives [13–15]. Recently, many studies have been carried out on replacing synthetic acaricides with new, safer agents, due to the risk of developing tolerance, toxicity and harmfulness to the natural environment associated with their overuse [16–21].

This review presents examples of currently used methods to control mites, including chemical and other measures. We aimed to present promising studies by various authors on the use of natural substances, biological strategies relying on bacterial and fungal microorganisms, as well as macro-organisms, including predatory mites and insects.

1.1. Life Cycle

T. urticae feeds mainly on the underside of the leaf [22]. After colonizing a new site, spider mites produce a silk web, which protects them against the negative effects of abiotic and biotic environmental factors and indicates the presence of the pest [23,24]. The silk web is also used by *T. urticae* for migration and is the carrier of a pheromone substrate [25–27]. Some plant species have leaves structures called leaf domatia, which are very eagerly colonized due to the microclimate promoting the development of spider mites [28].

Apart from the occurrence of webs, the presence of spider mites is evidenced by chlorotic discolouration on the leaves caused by feeding. Physical damage to leaf tissues disturbs the structure of the photosynthetic apparatus and photosynthesis, carbon dioxide assimilation, sugar metabolism and transpiration of the colonized leaves [29–33]. Significantly increased guaiacol peroxidase (GPX) activity and low level of catalase (CAT) activity were measured in *Ocimun basilicum* L. 'Purpurascens' (Lamiaceae) leaves infested by mites [34]. It is a species characterised by haplodiploid arrhenotoky, in which males develop from unfertilized eggs and are haploid, whereas females develop from fertilized eggs and are diploid [35]. The life cycle consists of the egg, larvae, quiescent larva (protochrysalis), protonymph, quiescent protonymph (deutochrysalis), deutonymph, quiescent deutonymph (teleiochrysalis), and sexually mature individuals: males and females. Males guard quiescent deutonymph females before they reach maturity, or juvenile females, and then fertilize them [35]. Regev and Cone [36–38] identified farnesol, nerolidol, geraniol, and citronellol as the components of sex pheromones in quiescent deutonymph females. Females mate only once, while males mate multiple times [39], preferring unrelated females [40]. The length of the life cycle and the development of the population depends on the temperature, the type of host plant on which it develops, and plant health [41,42]. The dynamics of its population also depend on the light intensity at the site of plant growth. Exposure to light intensity from 50 to 450 µmol $m^{-2} \cdot s^{-1}$ increases its fertility and decreases its mortality [43]. Under optimal conditions, their life cycle is shorter than 10 days, and one female can deposit more than 100 eggs [44,45]. During the growing season of the host plant, the population of *T. urticae* may increase by many times. Its growth population, apart from environmental conditions, is also influenced by the type of social interactions between females and males, modifying female fertility [46].

T. urticae only moves relatively short distances on its own. It mainly migrates by wind-drift dispersal [47]. When food availability is low, silk balls, i.e., aggregates formed mainly by sexually immature females, can be observed on apical parts of plants. Silk balls are dispersed to new sites where females establish new colonies [48,49]. Females can go into the state of diapause. During this period, they do not feed or deposit eggs. Differences with respect to diapause have been observed between populations from different geographic regions [50,51]. Diapausing females are more tolerant to lower temperatures [52]. They are characterized by a different metabolism of amino acids, sugars and proteins compared to summer females [53,54] and a different expression of genes determining digestion and detoxification, cryoprotection, carotenoid synthesis and the organization of the cytoskeleton [55]. A difference in the termination of the diapause in females collected at different times of winter has been observed [56]. Diapause in *T. urticae* females is associated with the reorganization of their metabolism and physiology in short-day regions, low ambient temperatures and limited food availability. Diapause in females is a strategy enabling survival in these unfavourable conditions.

1.2. Harmfulness

About 10% host plants infested by *T. urticae* are crops [57], including economically important crops in different regions of the world [58–61]. The intensive feeding of mites combined with a rapid increase in population size have a negative effect on the physiology of the whole plant, as well as the yield size and quality [58,62]. Muluken et al. [63] observed the complete destruction of potato plants in fields. Nyoike and Liburd [64] reported 50 to 80% loss in strawberry yield, while Jayasinghe and Mallik [65] reported up to 50% loss in tomato yield. This high loss in yield has been explained by pest invasion in the early stages of plant development, which was observed in *Cucumis sativus* L. (Cucurcitaceae) [66], cotton [67], tomato [65], and potato [68]. Spider mites are also harmful to sugar beet *Beta vulgaris* L. (Chenopodiaceae) grown in Poland [69]. For several years, large populations of this pest have been observed in plantations in central Poland, especially in Wielkopolskie, Kujawsko-Pomorskie, Łódzkie, Lubelskie, and parts of Mazowieckie provinces. It is a region with a large acreage of sugar beet crops, as well as agrometeorological conditions favourable for the development of the pest during the growing season (dry springs, high summer temperatures 25–30 °C and low precipitation 0−200 mm) [70].

Symptoms of damage caused by mites are initially observed on field margins, and with time they appear in patches all over the field. *T. urticae* causes premature yellowing and drying of the leaves. The feeding of mites that suck out the parenchymal tissue is visible on both sides of the leaf of sugar beet plants. As a result of intense pest feeding, small, bright spots in a mosaic pattern develop on the upper side of the leaf. The underside of the leaves is covered by a silk web with different developmental stages of the spider mite. The symptoms of early pest feeding are very often underestimated and mistaken for symptoms caused by viruses, nematodes or drought. The increase in twospotted spider mite population and further feeding cause leaf malformation and a web occurs on the plant apex. Plants wilt, turn brown and eventually die back. In the climate of Poland, *T. urticae* might produce from 4 to 6 generations during one growing season. When temperatures are favourable (25–30 °C), which often happens in late spring and summer, a single generation might develop in just 8 days [69]. The decrease in the root yield caused by intensive feeding of twospotted mite on sugar beet may be from 20 to 50%, and the sugar content in the roots may be reduced by up to 2% [69,71,72].

2. Available Methods for the Control of *T. urticae*

2.1. Chemical Control of T. urticae

Currently, the most popular method for the control of spider mites relies on the use of synthetic acaricides. Treatments should be performed based on systematic monitoring. According to regulations on integrated pest management, plants should be sprayed when threshold values of economic injury are exceeded and when the pest population cannot be reduced by growing arachnid-tolerant plants or using biological methods. If several treatments are necessary, they should be performed with products from different chemical groups, representing different modes of action. Phytophagous mites from the Tetranychidae family are a very specific group of crop pests. Their presence on crops often goes unnoticed until the damage caused by feeding causes significant economic losses. In practice, acaricides should be used when a greater number of mites is observed, and a silk web occurs on different plant organs. Moreover, these pests may produce up to several generations during the growing season and very quickly develop resistance to the active ingredients contained in synthetic acaricides. Table 1 presents selected products for the control of spider mites from among 14 chemical groups (15 active substances) available on the world market of plant protection chemicals. The presented acaricides are diverse in their mechanism of action. They affect the nervous system—neurotoxins (5)—inhibit the growth of mites or disturb their development (8), and inhibit lipid metabolism (2).

Table 1. Synthetic acaricides that have been used for controlling *T. urticae* worldwide.

Active Ingredient	Chemical Group	Mode of Action	Studies on Pest Resistance
Abamectin, Milbemectin	Macrocyclic lactones	Neurotoxin. Contact and gastric poison. Produces a translaminar effect and a limited systemic effect	[8,9,16,17,73–77]
Acequinocyl	Quinolines	Preinsecticide. Ovicidal action. Disrupts cellular respiration and ATP synthesis. Contact and gastric poison	[18,78]
Bifenazate	Carbazinates	Ovicidal action. Disrupts cellular respiration and ATP synthesis. Contact poison	[16,17,79]
Clofentezine	Tetrazines	Growth regulator. Toxic to eggs and larvae. Contact poison	[16,17]
Ethoxazole	Diphenyl oxazoline	Chitin synthesis inhibitor. Inhibits the moulting of mites. Toxic to eggs and larvae. Contact poison	[14,18]
Fenazaquin	Quinazoline	Disrupts cellular respiration. Contact poison	[19,78]
Fenpyroximate	Phenoxypyrazoles	Disrupts cellular respiration and energy metabolism in all mobile life stages of mites. Contact and gastric poison	[18]
Phosmet malathion	Organophosphates	Inhibits choline esterase activity. Neurotoxin. Contact and, to a lesser extent, gastric poison	[16,79,80]
Hexythiazox	Thiazolidines	Growth regulator. Toxic to eggs and larvae. Contact and gastric poison. The substance has a translaminar effect	[16,17]
Oxamyl	Carbamates	Acetylcholinesterase inhibitor. Neurotoxin. Contact poison. Has a penetrating and systemic effect.	[19,73,74]
Pyridaben	Pyridazinones	Disrupts cellular respiration. Contact poison.	[16,17,19,81,82]
Synthetic pyrethrins	Pyrethrins	Disrupt neural conductivity. Block sodium channels in nerve cells. Contact poison.	[16,17,83]
Spirodiclofen	Tetronic acids	Inhibits lipid biosynthesis by inhibiting acetyl-CoA carboxylase. Contact poison.	[19,73,78]
Tebufenpyrad	Pyrazole derivatives	Neurotoxin. Contact and gastric poison. Has a translaminar effect and a limited systemic effect.	[16,17,78]

Many years of observations on the chemical control of spider mites revealed the presence of pest resistance. For example, since the 1970s, *T. urticae* has dominated in cotton grown in Australia, where resistance to acaricides used at that time was very quickly noted. Tolerance of *T. urticae* was also observed in cotton and bean plantations treated with insecticidal organophosphates [80].

The resistance of *T. urticae* to pyridaben, a substance from the pyridazinone class, was also investigated [16,17,81,82]. Pyridaben is a mitochondrial electron transport complex I inhibitor. The H110R mutation in the PSST subunit has been reported as a major factor in pyridaben resistance in the two-spotted spider mite, *T. urticae*. However, backcross experiments revealed that the mutant PSST alone conferred only moderate resistance. In contrast, inhibition of cytochrome P450 (CYP) significantly reduces resistance levels in many highly resistant strains. It was reported previously that maternal factors contributed to the inheritance of pyridaben resistance in the egg stage, but the underlying mechanisms

have not been explained. Itoh et al. [82] studied the combined effects of the PSST H110R mutation and candidate CYPs, as resistance factors on pyridaben resistance in *T. urticae*. Their study (2021) revealed that the maternal effects of inheritance of resistance in the egg stage were associated with CYP activity. Analysis of differential gene expression by RNA-seq identified CYP392A3 as a candidate causal factor for the high resistance level. The researchers concluded that the high pyridaben resistance levels are due to a synergistic or cumulative effect of the combination of mutant PSST and associated CYPs, including CYP392A3, but other yet to be discovered factors might also be involved [82].

Currently, *T. urticae* is defined as the major crop that is pest-resistant to most of the selective acaricides approved for its control, i.e., organophosphates, abamectin, clofentezine, hexythiazox, bifenthrin and chlorphenapil [16,17,83]. The control of spider mites is very difficult because, due to the emergence of several generations per year, the rapid development of resistance to chemical products has been observed in this species. In the practice of plant protection, various biological agents are increasingly used, including acarophages, biotechnological agents, or other methods based on natural substances [19,84,85].

2.2. Available Methods for the Control of T. urticae

Due to the policy aiming to reduce the use of synthetic pesticides, the purpose of which is to protect the natural environment and its biodiversity, researchers are looking for new, effective methods to limit the harmfulness of *T. urticae*. In this area of interest, studies are carried out on the development of biopesticides based on natural substances and the bionomy of host plants, on the effects of microorganisms, their metabolites, and beneficial organisms.

Previous studies have demonstrated that *T. urticae* populations develop resistance to major acaricides due to their short life cycle (8–12 days at 30–32 °C) and high fertility (90–110 eggs per female) [86]. Therefore, it is necessary to develop new, natural control methods as an alternative to chemical products. One example of such a novel approach is the use of intercropping systems to minimize resistance to pesticides [20,87,88], reduce pest population densities [87–90], increasing the diversity and efficiency of natural enemies [61,91–97] and to improve crop yield [61,88,97].

2.2.1. Natural Properties of Plants

One method to reduce the harmfulness of pests is to grow plants whose natural properties inhibit pest development. Numerous studies have demonstrated the intraspecific differences in the susceptibility of crop cultivars to infestation by *T. urticae*, e.g., grapevine *Vitis* L. [98], strawberry *Fragaria* spp. (Rosaeceae) [99,100], *Rosa* spp. (Rosaceae) [101,102], *Malus* spp. (Rosaceae) [103–106], *Phaseolus vulgaris* L. (Fabaceae) [107–112], *Cucumis sativus* L. [113,114], *Prunus persica* (L.) (Rosaceae) [115], *Glycine max* L.(Fabaceae) [116], *Solanum lycopersicum* (L.) [117,118], *Solanum melongena* L. (Solanaceae) [119]. Different susceptibility of cultivars to colonization by *T. urticae* may be due to physical aspects and result from the structure of the leaf blade, cuticle, and the presence of grandular and non-grandular trichomes, which secrete plant defence substances (secondary metabolites) or prevent *T. urticae* from colonizing leaves and feeding.

Secondary plant metabolites have been investigated in many experimental studies aimed at identifying effective and safe agents protecting against spider mites. Plant extracts may have a potential for the control of mites due to the content of secondary metabolites, such as terpenoids, alkaloids, flavonoids and polyacetylenes [120,121]. Moreover, plant extracts often contain mixtures of active substances which may delay or prevent the development of resistance [122]. In addition, when selecting potential pesticidal plant extracts, several properties need to be considered, including the efficiency of their low concentrations in mite control, and non-toxicity to other animals, so that they can be used safely in sustainable agriculture [123]. Extracts obtained from aboveground and underground parts of plants have a lethal effect on spider mites, change the conductivity in the nervous system

by influencing sodium channel transport [124], and have a deterrent/repellent effect and inhibit the egg-laying process [125–132].

So far, studies on the efficiency of *T. urticae* control have been carried out for more than 100 plant species from different botanical families, among which the largest number of plants studied represented Asteracae [133,134]. Yanar et al. [135] reported that the foliar application of alcoholic leaf extract from *X. strumarium* L. (Asteraceae) and *Anthemis vulgaris* L. (Asteraceae) caused 79.85 ± 0.83 and 76.63 ± 2.08% mortality in female two-spotted mites, respectively. Among natural pesticides, French marigold *Tagetes patula* Linn. (Asteracae) is considered an excellent species because it produces thiophenes and many polyacetylene compounds with a strong biocidal effect [136]. Antibacterial, antifungal, insecticidal and nematocidal activities of this plant species have been demonstrated in many studies [137–143], in addition to the effective control of ticks [87]. An experiment carried out by Ismail et al. [72] revealed that the marigold extract had toxic, ovicidal and repellent effects on *T. urticae*, and caused a 30−50% reduction in the number of deposited eggs. The deterrent and toxic properties of *Abrus precatorius* (Fabaceae) seed extracts were reported by Amer et al. [144]. The essential oils obtained from *Tanacetum vulgare* L. (Asteraceae) and *Artemisia absinthium* L. (Asteraceae) strongly increased the mortality of *T. urticae* [145]. Extracts from *Matricaria recutita* L. (Asteraceae), *Achillea millefolium* L. (Asteraceae), *Taraxacum officinale* L. (Asteraceae), and *Salvia officinalis* L. (Lamiaceae) strongly decreased the fertility, viability and feeding intensity of *T. urticae* [146,147]. Surface deposits on *Taxus baccata* L. (Taxaceae) needles removed by dipping in water had a detrimental effect on the total fecundity and oviposition period of *T. urticae* [148]. Many experimental studies have demonstrated that fragrances of phylogenetically distant plants are most effective in repelling certain pests on host plants [17,20,95–97]. When selecting potentially pesticidal plant extracts, several properties should be considered, including the efficiency of low concentrations in controlling mites, and lack of toxicity to other animals, ensuring safe use in sustainable agriculture [17]. One aspect of introducing and using plant extracts is their persistence and efficiency. The persistence and efficiency of a biopesticide can be improved by using new formulations, e.g., chitosan nanocapsules loaded with oil extracted from *A. millefolium*. In a study by Ahmadi et al. [149], this procedure significantly prolonged the acaricidal effect of the oil by controlling its release depending on the pH of the environment.

Based on the reported efficiency of natural substances, commercially available biopesticides have been developed and recommended for the control of *T. urticae* in many crops. Table 2 presents examples of plants as a source of natural secondary metabolites showing high biological activity. Particular attention was paid to those plants, the extracts of which were characterized by antifungal, antibacterial or anti-inflammatory properties.

Table 2. Plant protection products formulated on natural extracts from plants used for treatment *T. urticae* worldwide.

Active Ingredient/ Plant Extracts	Country	Plants	References
Abamectin 18 g	Poland	Eggplant (*Solanum melongena* L.), cucumber (*Cucumis sativus* L.), peppers (*Capsicum annuum* L.), tomato (*Solanum lycopersicum* L.), chrysanthemum (*Chrysanthemum* L.), rose (*Rose* L.), strawberry (*Fragaria* L.), raspberry (*Rubus ideus* L.), blackberry (*Rubus fructinosus* L.); tomato, rose, strawberry under covers	[150]

Table 2. *Cont.*

Active Ingredient/ Plant Extracts	Country	Plants	References
Abamectin	Australia	Adzuki bean (*Vinga angularis* (Willd.)), apple (Malus L.), blackberry, blackcurrant (*Ribes nigrum* L.), capsicum or pepper, custard apple (*Annona reticulata* L.), corkwood tree (*Duboisia* R.Br), fruiting vegetables excluding cucurbits (Cucurbitaceae), hops (*Humulus lupulus* L.), lychee (*Litchi chinensis* Bonn.), mung bean (*Vinga radiata* (L.)), navy bean (*Phaseolus vulgaris* L.), ornamentals, passion fruit (*Passiflora edulis* Sims.), pear (*Pyrus communis* L.), raspberry, snow pea (*Pisum sativum* L.), strawberry, sugar snap pea, sweet corn (*Zea mays* L.), tomato—field grown	[151–153]
Azadirachtin	Australia	African violet (*Saintpaulia ionatha* Saint Paul-Illaire), aster (*Aster* L.), azalea (*Rhododendron* L.), begonia (*Begonia* L.), chrysanthemum, daffodil (*Narcissus psudonarcissus* L.), dahlia (*Dahlia* L.), delphinium (*Delphinium* L.), geranium (*Geranium* L.), gladiolus (*Gladiolus* L.), hibiscus *Hibiscus rosa-sinensis* L.), iris (*Iris* L.), ivy (*Hedera* L.), lily (*Lilium* L.), lawn, lemon (*Citrus* L.), mandarin (*Citrus reticulata* Blanco), marigold (*Tagetes* L.), mushroom (*Agaricus bisporus* L.), nectarine (*Prunus persica* var. *nucipersica* (Suckow)), orange (*Citrus sinensis* (L.)), ornamentals, potting soil, rose, snapdragon (*Antirrhinum majus* L.)	[153]
Azadirachtin	Colombia	Artichoke (*Cynara cardunculus* var. *scolymus* L.), asparagus (Asparagus officinalis L.) avocado (*Persea americana* Mill.), blackberry, blueberry (*Vaccinium* L.), broccoli (*Brassica oleracea* var. *italica* L.), carnation cauliflower (*Brassica oleracea* L.), chili pepper, chrysanthemum, coffee (*Coffea* L.), cranberry (*Vaccinum macrocarpon* Aiton), eggplant, gooseberry (*Ribes uva-crispa* L.), granadilla *Passiflora ligularis* Juss.), grape (Vitis L.), grapefruit (*Citrus* x *paradisi* Macfad.), highbush berry (*Vaccinium corymbosum* L.), blueberry, lemon, lettuce (*Lactuca sativa* L.), lime, mandarin, naranjilla (*Solanum quitoense* Lam.), orange, ornamentals, passion fruit, pepper (*Piper nigrum* L.), pineapple (*Ananas comosus* (L.)), potato (*Solanum tuberosum* L.), rabbit eyeraspberry (*Vaccinium virgatum* Aiton.), rose, spinach (*Spinacia oleracea* L.), strawberry, sweet pepper, tangelo (*Citrus* x *tangelo* Ingram & Moore), tomato, tree tomato (*Solanum betaceum* Cav.)	[153]
Azadirachtin	Uganda	All crops	[153]
Azadirachtin, Pyrethrin natural	Portugal	All crops	[153]
Azadiractia indica L., *Pongamia pinnata* L. *Ricinus communis* L.	Uganda	All crops	[153]

Table 2. *Cont.*

Active Ingredient/ Plant Extracts	Country	Plants	References
Canola oil	Canada	African eggplant (*Solanum macrocarpon* L.), alfalfa (*Medicago sativa* L.), amur river grape (*Vitis amurensis* Rupr.), apple, apricot (*Pruns americana* (Scop.)), aronia berry (*Aronia arbutifolia* (L.)), ash (*Fraxinus* L.), asparagus (*Asparagus officinalis* L.), barberry (Berberis vulgaris L.), bayberry (*Myrica* L.), bean (*Phaseolus* L.), bearberry (*Arctostaphylos uva-ursi* (L.)), beet (*Beta vullgaris* L.), pepper, bilberry (*Vaccinium myrtillus* L.), birch (*Betula* L.), black raspberry (*Rubus occidentalis* L.), blackberry, blackcurrant (*Ribes nigrum* L.), blueberry, broccoli, buffalo berry (*Shepherdia argentea* (Pursh)), buffalo currant (Ribes aureum Pursh), bush tomato (*Solanum centrale* L.), cabbage (*Brassica oleracea* var. *capitata* L.), carrot (*Daucus carota* L.), cauliflower, celery (*Apium graveolens* L.), chard (*Beta vulgaris* L.), chayote (*Sechium edule* (Jacq.)), cherry (*Prunus avium* L.), chestnut (*Castanea* Mill.), omordi guava (*Ugni molinae* Turcz.), omordi waxgourd (*Benincasa hispida* (Thungb), chokecherry (*Prunus virginiana* L.), citron melon (*Citrullus caffer* Schrad.), cloudberry (*Rubus chameamorus* L.), cocona (*Solanum sessiliflorum* Dunal), crab apple (*Malus sylvestris* Mill.), cranberry, cucumber, cudrane (*Cudrania omordicate* (Carrière)), currant (*Ribes* L.), currant tomato (*Solanum pimpinellifolium* (L.)), dogwood (*Cornus florida* L.), edible honeysuckle (*Lonicera* L.), eggplant, elderberry (*Sambucus nigra* L.), elm (*Ulmus* L.), evergreen trees, firethorns (*Pyracantha* Roem.) flowering cherry (*Prunus serratula* (Lindl.)), peach, plum, foliage plants, garden huckleberry, geranium, goji berry (*Lycium chinense* L.), grape, groundcherry (*Physalis* L.), hawthorn (*Crateagus* L.), hazel tree (*Corylus* L.), highbush cranberry (*Viburnum trilobum* Marshal), holly (*Ilex* L.), hop, house plants, huckleberry (*Vaccinium* L. and *Gaylussacia* Kunth), jostaberry (*Ribes* × *nidigrolaria*), juneberry (*Amelanchier lamarckii* Lamarck), kale (*Brassica oleracea* L.), kiwi (*Actinidia chinensis* (Planch.)), lettuce, lilac (*Syringa vulgaris* L.), lingonberry (*Vaccinium vitis-idaea* L.), magnolia (*Magnolia* L.), maize, maple, martynia (*Martynia annua* L.), maypop (*Passiflora incarnata* L.), melon (*Cucumis melo* L.), omordica (*Momordica charantia* L.), mountain pepper berry (*Tasmannia lanceolata* (Poir.)), mulberry (*Morus* L.), muntries (*Kunzea pomifera* Muell.), muskmelon, naranjilla, native currant (*Acrotriche depressa* R.Br.), nectarine, oak (*Quercus* L.), okra (*Abelmoschus esculentus* (L.)), onion (*Allium cepa* L.), ornamentals, partridgeberry (*Mitchella repens* L.), pea, pea eggplant (*Solanum torvum* Sw.), peach (*Prunus persica* (L.)), pear, pecan (*Carya illinoinensis* (Wangenh)), pepper, phalsa (*Grewia asiatica* L.), pincherry (*Prunus pensylvanica* L.f.), pine (*Pinus* L.), plum (*Prunus domestica* L.), potato, privet (*Ligustrum* L.), prune (*Prunus* L.), pumpkin (*Cucurbita* L.), radish (*Raphanus sativus* L.), raspberry, redcurrant (*Ribes rubrum* L.), riberry (*Syzygium luehmannii* (F.Muell)), rose, roselle (*Hibiscus sabdariffa* L.), rutabaga (*Brassica napus* L.), salal (*Gaultheria shallon* Pursh), scarlet eggplant (*Solanum aetiopicum*), schisandra berry (*Schisandra chinensis* (Turcz.)), sea buckthorn (*Hippophae* L.), serviceberry (*Amelanchier* Medik.), sour cherry (*Prunus cerasus* L.), soybean (*Glycine max* L.), spruce (*Picea* L.), squash (*Cucurbita* L.), strawberry, sugar beet, sunberry (*Solanum retroflexum* Dunal), ycamore (*Platanus* L.), tamarillo (*Solanum betaceum* Cav.), tomatillo (*Physalis philadelphica* Lam.), tomato, tulip tree (*Liriodendron* L.), turnip (*Brassica rapa* subsp. *rapa* L), walnut (*Juglans* L.), watermelon (Citrullus lanatus (Thunb.)), wild raspberry (*Rubus occidentalis* L.), willow (*Salix* L.)	[153]

Table 2. *Cont.*

Active Ingredient/ Plant Extracts	Country	Plants	References
Eco oil	Australia	Capsicums, cucumbers, tomatoes	[153]
Extract of *Tithonia diversifola* (Hemsl.)	Colombia	Avocado (*Persea americana* Mill.)	[153]
Extract of *Quillay saponinas* Molina Non-saponin solids such as polyphenol salts and sugars	Colombia	Avocado, blackberry, blueberry, chirimoya (*Annona cherimola* Miller), cranberry, fig (Ficus carica L.), grape, grapefruit, guana (*Psidium guajava* L.), highbush blueberry, lemon, mandarin, mango (*Mangifera* L.), orange, ornamentals, papaya (*Carica papaya* L.), peach, plum, rabbit eye blueberry, raspberry, rose, sapodilla (*Manilkara zapota* (L.)), strawberry, sugar apple (*Annona squamosa* L.), tangelo, tomato	[153]
Fatty acids C14–C20–479.8 g	Poland	Cucumber, strawberry tomato under cover; chokeberry (*Aronia* Medik.), cranberry, honeysuckle, raspberry, blackberry, black currant, red currant, white currant, gooseberry (*Ribes uva-crispa* L.), cherry, plum, pear, tomato	[150]
Garlic extract, Pyrethrin natural	Uganda	All crops	[153]
Key lime extract, Olive extract	Peru	Asparagus, avocado, banana (*Musa* L.), blueberry, granada (*Punica granatum* L.), grapevine, lemon, mandarin, mango, plantain (*Plantago* L.), subtle lemon (*Citrus limon* (L.)), tangelo	[153]
Maltodextrin	Ghana	African pear, apple, avocado, banana, bean, bell pepper (*Capsicum annuum* L.), bean, blackberry, broccoli, brussels sprout (Brassica oleracea var. gemmifera L.), cabbage, carrot, cassava (*Manihot esculenta* Cranz.), cauliflower, cherry, chilli pepper, cocoa (*Theobroma cacao* L.), Coconut (*Cocos nucifera* L.), common bean, cucumber, eggplant, bean, garden egg (*Solanum melongena* L.), green bean, guava, hot pepper, indian spinach (*Basella alba* L.), jackfruit (*Artocarpus heterophyllus* Lam.), kale, kiwi, lemon, lettuce, lime, maize (*Zea mays* L.), mango, melon, nectarine, noni fruit (*Morinda citrifolia* L.), okra, onion, orange, papaya, pear, pepper, pineapple, raspberry, soursop (*Annona muricata* L.), soybean, spinach, strawberry, sugar apple, sweet pepper, sweet potato (*Ipomea batatas* L.), tangerine (*Citrus reticulata* L.), taro, tomato, watermelon, yam (*Dioscorea alata* L.)	[153]
Maltodextrin	Portugal	All crops	[153]
Maltodextrin	Spain	All crops	[153]
Pyrethrin natural	Uganda	All crops	[153]
Mineral oil	Canada	All crops	[153]
Orange oil 60 g	Poland	Blackberry, raspberry	[150]
Orange oil—58.96 g	Poland	Ornamental plants, peppers, tomato	[150]
Orange oil	Portugal	All crops	[150]
Organic antioxidant, Silicone polymer, Siloxane	UK	All crops	[153]
Paraffin oil—770 g	Poland	Apple	[150]
Paraffin oil	Portugal	All crops	[153]

Table 2. *Cont.*

Active Ingredient/ Plant Extracts	Country	Plants	References
Potassium salts of fatty acids	Canada	All crops	[153]
Potassium salts of fatty acids	Australia	Different crops	[152]
Pyrethrin natural	Canada	African violet, apple, aralia (*Aralia* L.), aster, asparagus, azalea, bean, begonia, beet, broccoli, cabbage, carrot, celery, chrysanthemum, cineraria (*Cineraria* L.), cucumber, dahlia, delphinium, dieffenbachia (*Diffenbachia* Schott.), eggplant, evergreen trees, fuchsia (*Fuchsia* L.), geranium, gladiolus, gloxinia (*Gloxinia* LHer), grape, herbs, house plants, impatiens (*Impatiens* L.), iris, ivy, lantana (*Lantana* L.), lettuce, marigold, neanthe bella palm (*Chamaedorea elegans* Mart), onion, ornamentals, pea, pepper, petunia, potato, radish, rose, snapdragon, squash, tomato, turnip	[153]
Pyrethrin natural	Uganda	All crops	[153]
Rapeseed oil	Portugal	All crops	[153]
Rapeseed oil	UK	All crops	[153]
Urtica sativa L. extract	Portugal	All crops	[153]
Urtica sativa extract	Spain	All crops	[153]
Urtica sativa extract	Germany	All crops	[153]
White mineral oil	Ghana	African pear, apple, avocado, banana, bean, bell pepper, bean, blackberry, cabbage, carrot, cassava, cherry, chilli pepper, coconut, cucumber, eggplant, garden egg, guava, hot pepper, Indian spinach, jackfruit, kiwi, lemon, lettuce, lime, mango, melon, nectarine, noni fruit, okra, onion, orange, papaya, pear, pepper, pineapple, raspberry, soursop, soybean, spinach, star apple (*Chrysophyllum caimito* L.), strawberry, sugar apple, sweet pepper, sweet potato, tangerine, taro, tomato, watermelon, yam	[153]

Findings from laboratory studies have been successfully used in crop field trials. One example of such a novel approach is the use of intercropping systems to minimize resistance to pesticides [20,88]. *Allium sativum* L. 'Iandrace' (Amaryllidaceae) intercropped with strawberry (one, two and three garlic rows among the strawberry rows) caused a 44 to 65% reduction in the number of mobile forms of *T. urticae* [92]. The number of *T. urticae* eggs decreased by 38, 43 and 64%, respectively. This effect was attributed to sulfur compounds such as diallyl disulfide or diallyl trisulfide that were identified in garlic essential oil. Intercropping Chinese chive *Allium tuberosum* Rottler ex Spred. (Amaryllidaceae), Rottler ex Sprengel, with strawberry decreased the mean number of mites per leaf. However, it did not reduce the number of deposited eggs [92]. Mohammadi et al. [154] conducted a promising study in which strip intercropping of green beans with garlic reduced the densities of *T. urticae* eggs and mobile forms during the growing season in different intercrop ratios compared with green bean sole crop. In addition to protective secondary metabolites, plants also synthesize protective bioproteins. In 2017, Santamaria et al. [155] identified the MATI (mite attack triggered immunity) protein in *Arabidopsis thaliana* L. (Brassicaceae) plants closely related to resistance to *T. urticae*. The study revealed that *T. urticae* caused greater damage to *Arabidopsis* leaves in MATI knockdown mutants compared to Col-MATI overexpressing line.

2.2.2. Micro- and Macro-Organisms for the Control of *T. urticae*

Bacteria

The use of bacteria for the control of *T. urticae* is one of the research areas to develop an effective method for the control of the two-spotted spider mite. Many studies have demonstrated that *Pseudomonas aeruginosa* (Schroeter) caused a 100% mortality of adult females *T. urticae* after 72 h at a concentration of 10^7 cfu mL^{-1} by spraying application. Treatment with *Bacillus subtilis* (Ehrenberg) resulted in approximately 80% mortality, and *Lysinibacillus spaericus* (Meyer and Neide) slightly more than 95% [156]. Golec et al. [157] reported that products based on *Chromobacterium subtsugae* Martin et al., strain PRAA4-1 (Grandevo DF2) and heat-killed *Burkholderia* spp. 92 strain A396 (91 Venerate EP) limited the growth of a *T. urtice* population after a single treatment during a single pest generation. Grandevo DF2 caused 50% mortality in nymphs and reduced the fertility of females that survived the application of this product. Treatments with *Streptomyces avermitilis* (Burg et al.) and *B. thuringiensis* Berliner 1915 caused 90–100% mortality in females and 91–99% mortality in nymphs, respectively [158]. The pathogenicity of the bacteria is based on adhesion, which can increase the penetration of proteases, chitinase, lipase and hydrolase across the epidermis and natural openings in the *T. urticae* body, leading to the rapid death of the pest. In addition, the deterrent effect of *Pseudomonas* strains could be explained by the production of secondary metabolites, including volatiles, which prevent *T. urticae* colonizing leaves [159].

Fungi

Attempts have also been made to use parasitic fungi for the control of spider mites. Satisfactory efficiency has been achieved for *Beauveria bassiana* (Bals.-Criv.), [160], *Metarhizium brunneum* Petch [161] and *Metarhizium anisopliae* (Metchnikoff) strain 442.99, *Hirsutella* spp., strain 457.99 and *Verticillium lecanii* (Zimm.) strain 450.99. For *B. bassiana* (Naturalis-L) a 98% reduction in the number of eggs, juvenile and adult forms of *T. urticae* on tomato plants was observed [162].

One method to reduce the harmfulness of *T. urticae* relies on the use of fungal fermentation products: milabamectin and abamectin. These compounds are produced by soil fungi from the actinomycetes group: *Streptomyces hygroscopicus* subsp. *aureolacrimosus* (Jensen) and *Streptomyces avermitilis* (ex Burg). Abamectin is commercially available in products for the control of *T. urticae* in a wide range of vegetables, fruit shrubs and ornamental plants (Table 1). In recent years, resistance to this substance has been observed among *T. urticae* populations in many regions of the world [75,163–166]. Among European populations, resistance to milabamectin and cross-resistance to both substances was observed [167].

Predatory mites

Mohammadi et al. [154] (2021) carried out studies on seven predators of *T. urticae*: *Stethorus gilvifrons* (Muhant), *Orius niger* (Wolff), *Neoseiulus zwoelferi* (Dosse), *Chrysoperla carnea* (Stepheus), *Geocoris punctipes* (Say), *Scolothrips sexmaculatus* (Pergande), and *Nabis pseudoferus* (Remane). Over two growing seasons, only two of these species, *S. gilvifrons* and *O. niger,* were the main predators of *T. urticae,* and they caused 20 to 45% reduction in *T. urticae* populations. Another predator of *T. urticae* is *Pronematus ubiquitus* McGregor. This mite also changes the biology of *T. urticae* and consequently females deposit a lower number of eggs on leaves that were previously colonized by *P. ubiquitus* [168].

One vital aspect of using bacteria and fungi to control *T. urticae* is their potential impact on beneficial predatory mites. Studies have demonstrated a significant role of timing when using microbial products. Despite their high efficiency, *Bacillus thuringiensis* Berliner and *Streptomyces avermitilis* (ex Burg), as well as fungus *Lecanicillium lecanii* had a negative effect on *Phytoseiulus persimilis* Athias-Henriot when products were applied on the same day. The release of predatory mites one day after treatment of plants with *L. lecanii* and 7 days after treatment of plants with *B. thuringiensis* or *S. avermitilis* had no negative effect on the survival of the introduced predators. These findings confirm the potential suitability of

entomopathogenic fungi and bacteria in combination with predatory mites in *T. urticae* biocontrol [158].

Insects

A study investigating the effects of naturally occurring insects in an organic strawberry crop demonstrated that *Anthocoris nemorum* (Linnaeus) may play a role in reducing *T. urticae* populations. Molecular analysis of the intestinal contents of these insects revealed the presence of *T. urticae* DNA [169]. The larval forms of the predatory thrips *Scolothrips longicornis* Priesner eat the eggs of *T. urticae*. Consumption increases as the temperature rises to 30 °C, and decreases at higher temperatures. *T. urticae* eggs are also consumed by female thrips most intensively before oviposition [170,171]. Laboratory studies revealed that a minute anthocorid, *Orius albidipennis* (Reuter), eats on average 7 females of *T. urticae* [172]. Investigation shown that ants have limiting effect on twospotted spider mite. In study under glasshouse conditions Miyagi et al. [173] and Osborne et al. [174] demonstrated that *Tapinoma melanocephalum* (Fabricius) is a significant predator of *T. urticae*.

The above-mentioned groups of micro- and macro-organisms have been used to develop commercially available biocontrol products. Products based on the activity of micro- and macro-organisms are presented in Table 3.

Table 3. Micro- and macro-organisms used in plant protection products for treatment *T. urticae* worldwide.

Biological Group	Species	Country	Crops
Bacteria	*Bacillus thuringiensis* Berliner, *Pseudomonas fluorescens* (Flugge)	Bangladesh	Tea
Fungi (entomopathogenic fungi)	*Beauveria bassiana* (Bals.)	Australia, Bangladesh, Uganda, Poland	Permitted for use on all crops
	Metarhizium anisopliae (Metchnikoff)	Kenya	Maize, ornamentals, rose
		Uganda	Permitted for use on all crops
	Paecilomyces fumosoroseus (Wize)	Colombia	Permitted for use on all crops
	M.anisopliae, *Paecilomyces lilacinus* (Thom)	Chile	Permitted for use on all crops
	Verticillum lecanii (Zimmerman)	Uganda	Permitted for use on all crops
Mites	*Amblydromalus limonicus* (Gharma & McGregor)	Germany, Portugal, Spain	Permitted for use on all crops
	Amblyseius andersoni (Chant)	Canada, Germany, Portugal, Spain, UK	Permitted for use on all crops
	A. andersoni	Kenya, UK	Ornamentals, Rose
	Amblyseius californicus (Moq.)	Kenya, Uganda, UK	French bean, ornamentals, rose, vegetable
	Amblyseius spp.	Canada, Chile, Germany, Portugal, Spain, UK	Permitted for use on all crops
	A. swirskii Athias-Henriot	Canada, Germany, Poland, Portugal, Spain, UK	Permitted for use on all crops
	Amblyseius sp., *Transeius montdorensis* (Schicha)	Portugal, Poland	Permitted for use on all crops

Table 3. *Cont.*

Biological Group	Species	Country	Crops
	Neoseiulus californicus McGregor	Australia, Bangladesh, Canada, Chile, Germany, Peru, Poland, Portugal, Spain, Uganda, UK	Permitted for use on all crops
	Hypoaspis miles Berlese	Canada	Permitted for use on all crops
	N. californicus	Kenya	Ornamentals, rose
	N. cucumeris (Oudemans)	Canada, Chile, Germany, Poland, Portugal, UK	Permitted for use on all crops
	Phytoseiulus persimilis Athias-Henriot	Australia, Canada, Chile, Germany, Peru, Portugal, Spain, Uganda, UK	Permitted for use on all crops
	Phytoseiulus macropilis (Banks)	Bangladesh	Permitted for use on all crops
	Ph. persimilis	Kenya, Poland	French bean, ornamentals, rose, vegetables, tomatoes
	Transeius sp.	Germany, Portugal, Spain, UK	Permitted for use on all crops
	Tyflodromus sp.	Australia	Permitted for use on all crops
Insects	*Chrysoperla carnea* Stephens	Canada, Poland, UK	Permitted for use on all crops
	Chrysoperla sp.	Chile	Permitted for use on all crops
	Dalotia coriaria (Kraatz)	Canada	Permitted for use on all crops
	Dicyphus hesperus Knigth	Canada	Permitted for use on all crops
	Feltiella acarisuga (Vallot)	Canada, Germany, Poland, Portugal, Spain	Permitted for use on all crops
	Macrolophus pygmaeus (Rambur)	UK, Poland	Permitted for use on all crops
	Macrolophus caliginosus Wagner	UK, Poland	Permitted for use on all crops
	Oligota pygmaea Solier	Chile	Permitted for use on all crops
	Orius insidiosus (Say)	Canada	Permitted for use on all crops
	O. tristicolor (White)	Chile	Permitted for use on all crops
	O. insidiosus	Chile	Permitted for use on all crops
	Orius spp., *Orius leavigatus* (Fieber)	Poland, UK	Permitted for use on all crops
	Parastethorus histrio (Chazeau et al.)	Chile	Permitted for use on all crops
	Stethorus punctillum (Weise)	Canada, Portugal, Spain	Permitted for use on all crops
	Coccinella transversalis Fabricius, *Hippodamia vareigata* (Goeze)	Australia	Permitted for use on all crops
	Parastethorus-Oligota	Chile	Permitted for use on all crops
	H. variegata, *Hyppodamia convergens* Cassey, *Adalia angulifera* (Musland), *A. bipunctata* (Linnaeus), *Eriopis connexa* (Germar)	UK	Permitted for use on all crops
Insects and mites	*Feltiella acarisuga* (Vallot), *Transeius montdorensis*	UK	Permitted for use on all crops

3. The Effect of Climate Change and the Expansion and Development of Spider Mites in the Future

The climate change observed for several decades will certainly affect the role of spider mites as crop pests. According to the current climate change scenario, *T. urticae* shortens its life cycle in dry and hot conditions, produces more generations per year, and broadens its host range [175]. Climate change models predict that the frequency, intensity and duration of heat waves will increase over the next two decades. Warming may promote the spread of not only *T. urticae* in the regions where the species is present, but also create conditions for the development of spider mites that so far are normally found in areas of warmer climate, e.g., the tropical species *Tetranychus evansi* Baker & Pritchard, 1960 [176,177]. Unfavourable winter temperatures do not rule out the possibility of this pest's survival on crops under cover. Currently, *T. evansi* has the status of an invasive species. Heat waves might have a profound impact on the efficiency of biological agents for the control of the spider mite [178]. High temperatures might influence the biology of the biocontrol agent, ranging from postponing oviposition to manipulating offspring quantity via egg number and quality via egg size. Such species-specific responses of biocontrol agents to heat stress may also affect their success in controlling spider mites.

Apart from the temperature, wind plays an important role in the dispersal of spider mites. Findings by Narimanov et al. [179] confirmed that strong electrical fields in the air elicit pre-dispersal behaviour, and in combination with a light wind facilitate the dispersal of mobile forms and propagation of spiders to other areas where crops are grown. In their experimental study, the researchers emphasized that the employed strong electrical fields played a rather supplementary role in spiders' dispersal, with wind remaining the most influential factor.

Current climate change is expected to improve the occurrence and spread of *T. urticae* in many cultivated plant species. Currently, the role of modern plant protection is to provide effective methods to control pests and to deliver solutions that minimize negative effects on the natural environment. Biological control methods are in line with the European Green Deal strategy, and they rely on the use of microorganisms, including entomopathogenic fungi, predators, or natural plant extracts and secondary metabolites, which create a natural barrier to the increased pressure of twospotted spider mites. Biological control treatments as an alternative to new chemicals used to control mites depend on a number of biotic and abiotic factors. Detailed ecological studies are required to investigate the interactions between the environment and its individual components, and to explain the bionomy of spider mites.

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