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Profile

Biology and Management of *Varroa destructor* (Mesostigmata: Varroidae) in *Apis mellifera* (Hymenoptera: Apidae) Colonies

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Abstract

Varroa mite (*Varroa destructor* Anderson and Trueman) infestation of European honey bee (*Apis mellifera* L.) colonies has been a growing cause of international concern among beekeepers throughout the last 50 yr. *Varroa destructor* spread from the Asian honey bee (*Apis cerana* Fabricius [Hymenoptera: Apidae]) to *A. mellifera* populations in Europe in the 1970s, and subsequently traveled to the Americas. In addition to causing damage through feeding upon lipids of larval and adult bees, *V. destructor* also facilitates the spread of several viruses, with deformed wing virus being most prevalent. Several sampling methods have been developed for estimating infestation levels of *A. mellifera* colonies, and acaricide treatments have been implemented. However, overuse of synthetic acaricides in the past has led to widespread acaricide resistant *V. destructor* populations. The application of Integrated Pest Management (IPM) techniques is a more recent development in *V. destructor* control and is suggested to be more effective than only using pesticides, thereby posing fewer threats to *A. mellifera* colonies. When using IPM methods, informed management decisions are made based upon sampling, and cultural and mechanical controls are implemented prior to use of acaricide treatments. If acaricides are deemed necessary, they are rotated based on their mode of action, thus avoiding *V. destructor* resistance development.

Key words: Integrated Pest Management, deformed wing virus, damage, sampling, treatment

Varroa destructor (Anderson and Trueman) is now believed to be the leading cause of colony collapse in *Apis mellifera* (L.) populations (Rosenkranz et al. 2010). With the exception of Australia, and several isolated island locations, *V. destructor* infestations have reached near-global populations (Locke 2016). The spread of *V. destructor* and associated viruses heavily influence colony collapse (Chen and Siede 2007). This pest profile will firstly discuss *V. destructor* biology, including morphology, life stages, and damage. Secondly, it will detail *V. destructor* sampling and treatment practices, a history of acaricide use, and the development of Integrated Pest Management (IPM) methods for control of these devastating ectoparasites.

Biology of *V. destructor*

The lifecycle of *V. destructor* takes place in two stages: an adult traveling stage, during which adult female mites feed upon adult bees (Ramsey et al. 2018), and a reproductive stage, which takes place within capped brood cells (Rosenkranz et al. 2010, Fig. 1). Morphological characteristics of each stage will be included below, along with a description of *V. destructor* activity during each stage.

Adult Traveling Stage

Adult traveling stage mites often change hosts or are groomed off by their hosts (Delfinado-Baker et al. 1992). Because this stage poses many inherent risks to the mites, it is thought that the adult traveling stage must be physiologically important (Xie et al. 2016). It has been suggested that this stage is necessary for spermatozoa capacitation, which takes approximately 5 d (Ziegelmann et al. 2016). However, the adult traveling stage can last for months, since these mites can overwinter on adult bees (Boecking and Genersch 2008). Nurse bees are also preferred, which, in light of recent research, is likely due to their larger fat bodies, in comparison to other adult bees (Ramsey et al. 2018). Transfer of *V. destructor* between colonies can take place through robbing, drifting of drones, and worker bee homing errors (Seeley and Smith 2015). Combining hives, transferring food stores between hives, and high bee densities, also facilitate the transfer of *V. destructor* between colonies (Fries and Camazine 2001).

The preferred position of *V. destructor* during the adult traveling stage has been shown to be at the third abdominal segment, preferentially on the left side of the bee (Ramsey et al. 2018). After emerging

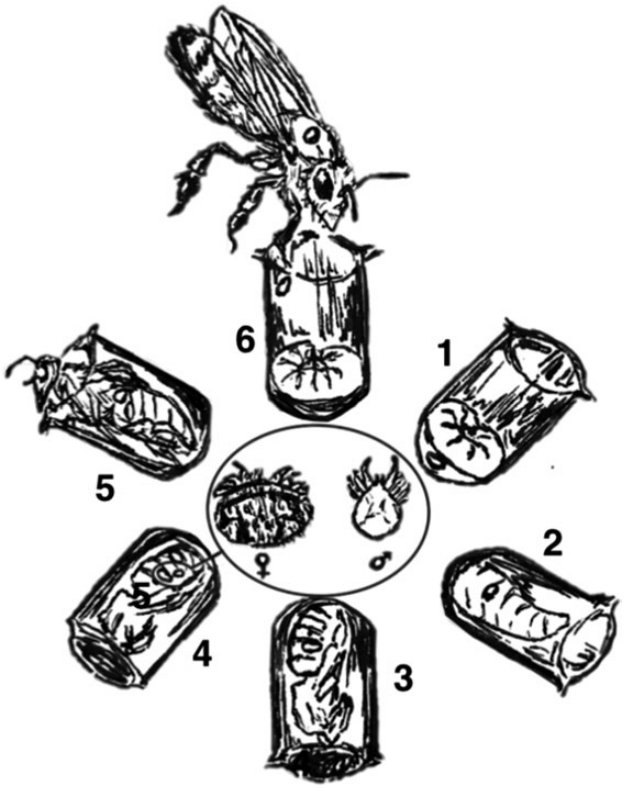

Fig. 1. *Varroa destructor* life cycle: 1) the female mite is transported to brood cell by nurse bee and 2) hides in brood food until 3) the prepupa stage, when feeding begins. 4) Laying of the male egg takes place after approximately 60 h, followed by female eggs every 30 h. 5) Mites undergo two developmental stages (protonymph and deutonymph), reach maturity, and mate. 6) Then the foundress and mature females exit on adult bee.

on their hosts, it was observed in one study that approximately 50% of the mites on newly emerged worker bees, and 80–90% of the mites on drones, transferred to a new host bee (Kuenen and Calderone 1997). A general distribution of 1–2 mites per bee is most often observed, with unusual cases of 3–4 mites on a single bee (Fernandez et al. 1993). Newly emerged bees are generally preferred hosts because of their frequent access to brood. However, pollinators are sometimes chosen, as they can carry mites to different colonies, especially when their colony is in the process of dying (Kuenen and Calderone 1997).

Reproductive Stage

Varroa destructor ontogenesis takes place in approximately 5.8 d in females and 6.6 d in males (Martin 1994), and is comprised of four distinct life stages, including egg, protonymph, deutonymph, and adult (Rosenkranz et al. 2010). The reproductive life stage of *V. destructor* begins when chemicals and kairomones draw female mites to enter the brood cell and hide within the brood food (Boecking and Genersch 2008). They remain inactive until the cell is capped, and the bee larva enters the prepupa stage, which takes approximately 60–70 h (Boecking and Genersch 2008). Host signals from *A. mellifera* L5 larvae, which are thought to be either nutritional factors or volatiles, cue the laying of an unfertilized male egg (Garrido and Rosenkranz 2003). The male egg is followed by a fertilized female egg, approximately 30 h later (Rehm and Ritter 1989), after which three other female eggs may be laid at 20- to 32-h intervals (Martin 1994). Males and nymphal female mites do not leave the cell and cannot survive outside of capped brood cells (Rosenkranz et al. 2010). Though not generally observed, it has been noted that up to three female mites could survive to adulthood under ideal circumstances (Rehm and Ritter 1989), and some have speculated that up to four fertilized females may mature, based on bee development time (Donze and Guerin 1994). It is thought that up to seven eggs may be laid in drone brood, while a maximum of six eggs may be laid in worker brood (Infantidis 1983).

Feeding Damage

After emerging from their eggs, *V. destructor* mites go through protonymph and deutonymph stages, as is seen in general mite development (Boecking and Genersch 2008). These stages are further subdivided by an initial mobile phase, followed by an immobile pharate phase that occurs before molting (Donze and Guerin 1994), and referred to as the protocrysalis and deutocrysalis, respectively (Ziegelmann et al. 2013). *Varroa destructor* mothers exhibit parental care in providing a single feeding hole in the cuticle of the bee pupae, usually on the fifth abdominal sclerite, which is located near a fecal accumulation site and facilitates easy travel between the two areas (Donze and Guerin 1994). The feeding hole is critical for mite development, since the chelicerae of *V. destructor* female nymphs are too soft to penetrate the cuticle, and male nymphs have chelicerae that are modified as spermodactlys, which also cannot pierce the cuticle (Donze and Guerin 1994). Only one feeding area and fecal accumulation area are created on bee pupae, even when multiple *V. destructor* females reproduce in the same cell, to reduce the risk of the pupae hemorrhaging and drowning the mites (Donze and Guerin 1994). The continuously open feeding hole also presents another opportunity for infection (Kanbar and Engels 2003).

After their second molt, the nymphs reach adulthood and are ready to mate. Females can mate multiple times with the male if other females do not continue to arrive at the fecal accumulation site, where fertilization takes place (Donze et al. 1996). It has been shown that male mites have a preference for the most recently matured females, which helps ensure that the maximum number of mites can be fertilized in the time available while the cell is capped (Ziegelmann et al. 2013). The reproductive stage ends when the adult bee exits the cell carrying the mother and mature daughter mites, leaving the male and immature females to die in the abandoned cell (Boecking and Genersch 2008).

Morphology

Though *V. destructor* males and females both have two clearly defined body sections, the idiosoma (dorsal and ventral shields) and gnathostoma (mouthparts; Rosenkranz et al. 2010), differentiation between the sexes is quite simple (Infantidis 1983). *Varroa destructor* adult males are pale yellow in color, with oblong, triangularly shaped bodies (De Jong et al. 1982), and longer legs than female mites (Infantidis 1983). Males are also much smaller than females, with average body widths and lengths of approximately 0.700 and 0.715 mm, respectively (De Jong et al. 1982).

Varroa destructor adult females are generally 1.1 mm wide (Fig. 2), and approximately 1.6 mm long, although body size can be highly variable between *V. destructor* populations (Maggi et al. 2012). Females are reddish-brown in color (De Jong et al. 1982) and they are covered with small bristling setae both dorsally and ventrally (Oudemans 1904), which help them stay attached to their hosts (Kirrane et al. 2012). Adult female mites have an ellipsoid, flattened body shape (Rosenkranz et al. 2010), with specialized host adherence structures called apoteles on their legs (De Ruijter and Kaas

1983). *Varroa destructor* females may reproduce up to seven times and can lay up to 30 eggs throughout their lifetime (Ruijter 1987).

Taxonomy

Varroa destructor was initially described by A. C. Oudemans in 1904 as *V. jacobsoni* (Oudemans 1904), and eventually re-described as V. destructor (Anderson and Trueman 2000). *Varroa destructor* was not correctly differentiated from *V. jacobsoni* until 2000 by Anderson and Trueman (Anderson and Trueman 2000). They classified six haplotypes of *V. jacobsoni* that varied in shape, were reproductively isolated, and were found infesting *A. cerana* colonies in mainland Asia as *V. destructor* (Anderson and Trueman 2000). Confirmation of species identification was achieved through sequencing of the mitochondrial DNA of the various *Varroa* species (Anderson and Trueman 2000, Evans and Lopez 2002, Gajićé et al. 2016). Although *V. jacobsoni* can also be found on *A. mellifera*, it is transient, as *V. jacobsoni* is only known to reproduce when living in *A. cerana* colonies (Anderson and Sukarsih 1996). The major phenotypic difference between *V. jacobsoni* and *V. destructor* is the larger body size observed in *V. destructor* specimens (Anderson and Trueman 2000).

Host Species and Damage

Because *A. cerana* was able to evolve along with *V. destructor*, this allowed for development of host defenses that *A. mellifera* does not possess (Locke 2016). *Apis cerana* demonstrates a high level of hygienic behavior that efficiently removes mites, along with uncapping, removing, and entombing of infested brood during mite reproduction (Rath 1999). *Varroa destructor* also faces reproductive limitations in *A. cerana* colonies, as it can only successfully reproduce on *A. cerana* drone brood (Boot et al. 1999) due to the efficient removal of infested worker brood (Rath, 1993). It is suspected that the spread of *V. destructor* to *A. mellifera* took place via queen and colony transport from Asia into Europe in the early 1970s (De Jong et al. 1982). By 1975, *V. destructor* damage was observed in eastern and western Europe, North Africa, and most of South America (De Jong et al. 1982). *Varroa destructor* infestations are now a near-global occurrence (Fries et al. 1994).

Although *V. destructor* was historically believed to feed only upon hemolymph, recent evidence has shown that damage is instead inflicted through lipid feeding (Ramsey et al. 2018). Feeding on larval, pupal, and adult bees weakens the host and reduces host immunity (Shen et al. 2005). Mite feeding also facilitates the transmission of viruses and bacteria (Ramsey et al. 2018), which can lead to the development of parasitic mite syndrome (Tantillo et al. 2015). Parasitic mite syndrome can be identified through the presence of diseases that are known to be transmitted by *V. destructor* (Tantillo et al. 2015). Of the 18 known honey bee viruses, six most commonly observed include: deformed wing virus, black queen cell virus, sacbrood virus, Kashmir bee virus, acute bee paralysis virus, and chronic bee paralysis virus (Chen and Siede 2007), deformed wing virus is now considered to be the most frequently detected (Tentcheva et al. 2004; Fig. 3).

Deformed Wing Virus

Deformed wing virus is a positive-strand RNA virus with three master variants (types: A, B, and C), and has been identified in all *A. mellifera* life stages (Kevill et al. 2017). Deformed wing virus tends to be concentrated in the head and abdominal regions of adults (Shah et al. 2009), but it can be isolated in other body areas, such as the thorax and wings (Lanzi et al. 2006). It has also recently been shown that the same colonies may be infected by more than one strain of deformed wing virus simultaneously (Jamnikar-Ciglenecki et al. 2019). Deformed wing virus can be transferred vertically to eggs laid by infected queens and transmitted horizontally through colonies via infected honey, pollen, and, potentially, feces (Chen et al. 2006). Although *V. destructor* acts as a vector for deformed wing virus, replication of deformed wing virus within these mites has not yet been confirmed (Jamnikar-Ciglenecki et al. 2019). Aside from the wing deformities that characterize this virus, symptoms of deformed wing virus can also include paralysis,

Fig. 2. *Varroa destructor* traveling stage female on *A. mellifera* worker thorax.

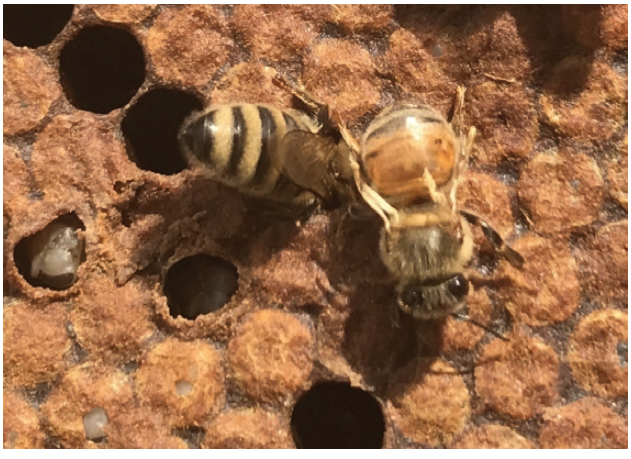

Fig. 3. *Apis mellifera* worker highlighting the deformed wings seen in severe cases of deformed wing virus.

abdominal bloating, rapid death of emerging bees (Iqbal and Mueller 2017), and learning deficiencies (Lanzi et al. 2006). It has also been observed that generally less than 1% of bees with deformed wing virus display wing deformities, which means that by the time symptoms are observed, much of the colony may already be diseased (Lanzi et al. 2006), though symptomatic *A. mellifera* have been shown to have the highest viral loads (Brettell et al. 2017). Additionally, the number of symptomatic bees seen in a colony has been shown to be an accurate predictor of overwintering colony losses (Dainat and Neumann 2013). If *V. destructor* infestations are not managed, colony death in 1–2 yr is inevitable (Rosenkranz et al. 2010).

Management of *V. destructor*

As *V. destructor* infestations have become a more prevalent global issue, numerous sampling methods and treatments have been developed and tested. Although treatment is necessary for colony collapse prevention, invasive sampling, high treatment costs, damage to bee products, and mite resistance all play a significant role in determining which methods should be implemented (Rosenkranz et al. 2010).

Sampling Methods

Four prominent *V. destructor* sampling methods have been developed for determining *V. destructor* population density. These range from invasive procedures, such as the uncapping of brood and the ether roll, to less invasive procedures, including the use of sticky boards and the powdered sugar shake method (Reuter and Spivak 2011).

Brood Uncapping and Removal

The uncapping and removal of brood is the only method that directly samples *A. mellifera* brood (Branco et al. 2006). This method involves removal of *A. mellifera* drone and worker brood with a cappings scratcher, or other uncapping tool (Thompson 2013). Once the brood are removed, they can be individually examined, and the incidence of adult female *V. destructor* mites per larva or pupa can be recorded (Branco et al. 2006). This method does not give a quantitative determination of how many mites are present in the hive (Morse 1999).

The Ether Roll Method

The other highly invasive method for estimating *V. destructor* infestation is the ether roll method (Calderone and Turcotte 1998). Although procedures differ as to the number of bees to collect, 100 to 300 bees are generally collected by moving a wide-mouthed glass jar along the side of a frame of brood comb (Morse 1999, Barlow and Fell 2006). Once the bees are collected, they are sprayed with a 2 s burst of diethyl ether. After the ether is added, all bees and mites die as the jar is shaken for 10 s, then rolled horizontally three times, leaving detached mites stuck to the sides of the jar (Calderone and Turcotte 1998). Because the ether roll may not remove all mites (Barlow and Fell 2006), the bees and mites are generally also soaked in ethanol and separated for counting (Calderone and Turcotte 1998). An infestation rate estimate can be determined by dividing the number of mites by the number of bees sampled (Calderone and Turcotte 1998).

Sticky Board Sampling

The least invasive method is performed by sampling mites off of a sticky board. Though sampling hive debris was another non-invasive method that was explored, using a sticky board was found to be preferable (Gulati et al. 2015). In this method, a sticky board, with a grid system is placed beneath the bottom hive body to catch dead or fallen mites over time, thus leading to a better knowledge of *V. destructor* population dynamics (Kretzschmar 2015). The sticky board is separated from the rest of the hive by a screened bottom board, which also helps improve hive aeration (Conrad 2008). Sticky boards can be purchased commercially, and they are often used in conjunction with an acaricide treatment, which causes the mites to fall more quickly (Calderone and Lin 2003). Subsampling from the grid on a sticky board can be the most efficient method when large numbers of mites are found, with population estimate methods depending on grid configuration (Calderone 1999). When not using the spatial patterning style sticky board, the total number of mites found after 24 h are counted, and treatment is recommended if over 40 mites are counted (Barlow and Fell 2006).

The Powdered Sugar Shake and Alcohol Wash Methods

The final major sampling method, the powdered sugar shake, combines the collection concept of the ether roll method, but replaces the ether and shaking solutions with powdered sugar, eliminating bee death in the sampling process. This non-lethal method may also serve to encourage new beekeepers, who may be concerned or intimidated by sampling, to sample and manage accordingly. During the development of this method, various inert dusts, including talcum powder, wheat flour, baking soda, corn starch, and fine sugar, were all tested; however, the greatest accuracy in mite detection was achieved with powdered sugar (Macedo et al. 2002). Powdered sugar has also been shown to have no negative effects on adult or brood bee health, does not detrimentally affect the respiratory system of the bees (Fakhimzadeh 2001), and even stimulates grooming behaviors (Stevanovic et al. 2012). As in the ether roll, the number of bees used in sampling may vary by researcher, and depending upon the collection device, but the concept remains the same. One recommendation for bee collection details the use of a ¼ cup (60 ml) measuring cup, which is known to hold up 200 (±25) bees (Spivak and Reuter, 2001). Once collected and deposited into a jar with a mesh-topped lid, bees are shaken in 1–2 tablespoons of powdered sugar for 1 min and allowed to rest for 1 min. Next, the jar is next inverted and dislodged mites are shaken out for 1 min (Reuter and Spivak 2011), then the mites are counted (Gregorc et al. 2017). The alcohol wash can also be performed using the above methods, which kills all bees sampled, but does allow the opportunity for individual bee examination (Morse 1999) The powdered sugar shake and the alcohol wash are now most highly recommended to beekeepers because of their high accuracy levels (Honey Bee Health Coalition 2018). However, the powdered sugar shake is preferable due to its nondestructive sampling procedures (Macedo et al. 2002).

Economic Threshold

The economic threshold for *V. destructor* varies based upon region and season, as *V. destructor* population size is heavily influenced by the presence of brood (Delaplane and Hood 1999). Depending upon climate, bees will undergo one or more colony cycles, in which the population will increase from dormancy, reach a peak, and then slowly decrease to a dormant state, with mite populations mirroring these cycles (Delaplane and Hood 1999, Honey Bee Health Coalition 2018). It is important to be aware of these seasonal differences, as a high mite load in a season with brood may not warrant the same treatment as a high mite load in a dormant season (Delaplane and Hood 1999, Honey Bee Health Coalition 2018). Another important consideration when determining at what levels to treat is honey loss, as many chemical treatments can contaminate

honey (Ellis 2001). Economic thresholds are generally reported as a number of mites per colony if a sticky board sampling technique is used, with one late summer economic threshold for an overnight sticky board being 59–187, though these estimates also depend on colony size (Delaplane and Hood 1999, Ellis 2001). When a powdered sugar shake or ether roll is performed, economic thresholds are generally reported as the number of mites per 100 adult bees, or percent infestation (Reuter and Spivak 2011, DeGrandi-Hoffman et al. 2014). Treatment is generally recommended when mite levels exceed 2–3% infestation, depending on the colony cycle (Honey Bee Health Coalition 2018).

Acaricides, Treatments, and Resistance

Chemical treatments for *V. destructor* are divided into two categories: 'hard' and 'soft' acaricides (Rosenkranz et al. 2010). The former is comprised of synthetic chemicals such as amitraz, coumaphos, and *tau*-fluvalinate, and flumenthrin, while the latter are organic acids and essential oils, including oxalic, formic, and lactic acids, as well as thymol and several other essential oils (Rosenkranz et al. 2010). These treatments are marketed under various trade names, and these treatments, along with their concentration levels, must be approved by the U.S. Environmental Protection Agency for in-hive use (Table 1; Rosenkranz et al. 2010, US EPA 2018).

Hard (Synthetic) Acaricides

Historically, the synthetic acaricides amitraz, coumaphos, and *tau*-fluvalinate were the most commonly used treatments for *V. destructor*, and overuse has predictably led to the development of acaricide resistance throughout the world (de Mattos et al. 2017). Synthetic acaricides have been found to detrimentally affect bees, slowing behaviors, such as grooming, and causing premature adult death (Berry et al. 2013). It has also been suggested that the high buildup of acaricide residues in beehives is a contributing factor in causing colony collapse (Mullin et al. 2010).

Historically, the most popular synthetic acaricide was the pyrethroid *tau*-fluvalinate, which functions through the disruption of the voltage-sensitive sodium channel in mites, and was effective through the early to mid 1990s, after which resistance was widely observed (Lodesani et al. 1994, Mozes-Koch et al. 1999, Johnson et al. 2010, Maggi et al. 2010, Hubert et al. 2014). The organophosphate coumophos, which inhibits acetylcholinesterase, was previously used to control *V. destructor* in both liquid and strip formulations (Elzen et al. 2004), but coumaphos has since been shown to decrease olfactory learning and memory (Williamson et al. 2013), reduce longevity in adults that were exposed as larvae (Wu et al. 2011) and accumulate in wax (Bajuk et al. 2017). Additionally, coumaphos has been shown to detrimentally impact sperm viability and queen health (Chaimanee et al. 2016). Amitraz is an octopamine receptor agonist and has become an unfavorable treatment option due to *V. destructor* resistance (Kamler et al. 2016).

Both coumophos and *tau*-fluvalinate have a half-life of 5 yr (although coumophos has also been estimated to have a half-life of only 115–346 d) in beeswax (Bogdanov 2004, Martel et al. 2007). Most synthetic acaricides are lipophilic, and as such, they build up quickly in wax, posing a threat to larval survival (Bajuk et al. 2017). Mixing of these synthetic acaricides can also lead to detrimental synergistic effects, such as *A. mellifera* mortality observed upon the mixing of coumaphos and *tau*-fluvalinate, that must be considered before combining treatments (Johnson et al. 2009).

Table 1. Treatments approved for use against *V. destructor* by U.S. EPA, table is modified table from www.epa.gov (2018)

Treatment	Active ingredient
ZOECON RF-318 APISTAN STRIP	Fluvalinate (10.25%)
APISTAN ANTI-VARROA MITE STRIPS	
FOR-MITE	Formic acid (65.9%)
AVACHEM SUCROSE OCTANOATE (40.0%)	Sucrose octanoate (40%)
API LIFE VAR	Thymol (74.09%), Oil of eucalyptus (16%), Menthol (3.73%)
MITE-AWAY QUICK STRIPS	Formic acid (46.7%)
FORMIC PRO	Formic acid (42.25%)
APIGUARD	Thymol (25%)
HOPGUARD II	Hop beta acids resin (16%)
Apivar	Amitraz (3.33%)
OXALIC ACID DIHYDRATE	Oxalic acid (100%)
CHECKMITE + BEE HIVE PEST CONTROL STRIP	Coumaphos (10%)

Soft (Organic) Acaricides

Soft acaricide treatments have been steadily increasing in popularity, as they rarely accumulate to harmful levels in hives and bee products (Rosenkranz et al. 2010). Oxalic acid that can be sprayed, trickled, evaporated into hives, or used as crystals, is thought to be preferable for use in autumn and winter months (Rademacher and Arz 2006). Lactic acid is also used in small apiaries during the autumn and winter, is administered by spray, but is a time-consuming treatment strategy (Kraus and Ben 1994). Formic acid is administered as a fumigant, inserted into hives on saturated pads or in gel pads (Elzen et al. 2004), or in gel packs, and is best used during summer months, or during a period of the year when average daily temperatures reach 15°C (Satta et al. 2005). These organic acids all occur naturally in honey (Kraus and Ben 1994, Rademacher and Arz 2006, Gunes et al. 2017); however, high levels of formic acid vaporization can be toxic to bees, therefore, acid concentrations and hive temperatures should be monitored while treatments are being administered (Elzen et al. 2004). It is recommended that day temperatures range between 10 and 33°C when formic acid strips are in use (Honey Bee Health Coalition 2018). Despite the risks, formic acid is also the only soft acaricide that is known to kill mites in *A. mellifera* capped brood cells, which makes it an attractive option (Fries 1991). The modes of action for these acids are unclear, but it is suspected that oxalic and lactic acid lead to mite death via solution acidity, and formic acid is thought to eventually interfere with *V. destructor* metabolism and respiration (Rosenkranz et al. 2010).

Many essential oils have also been tested for use in *V. destructor* control, however, thyme (thymol), marjoram, sage, wintergreen, clove, and turpentine (camphor) oil, are most commonly implemented, and have been somewhat successful (Imdorf et al. 1999). These treatments may be administered as fumigants, sprays, powders, saturated absorbent materials, or gels (Mondet et al. 2011). These essential oils are believed to be effective due to their neurological effects on *V. destructor* (Blenau et al. 2012). Tobacco extract was also shown to be an effective acaricide, especially when used in combination with clove oil (Mahmood et al. 2014). Thymol, purchased as Apiguard gel or powder, is the most commonly used essential oil. Thymol is considered to be more effective than *tau*-fluvalinate, which could be due to resistance (Ahmad et al. 2013) even though it can have different effects on bees of various ages and is still ineffective on mites in bee brood (Mondet et al. 2011).

Non-chemical Treatments

There have been many other control methods, more or less substantiated by subsequent research, that have been practiced by beekeepers throughout the years. Some researchers have attempted to mix together various essential oils, vitamins, minerals, and herbs for treatments, while others have shifted focus entirely to evaluating heat, water, and ultrasound control techniques (Rosenkranz et al. 2010, Gajger et al. 2013). Biological methods, such as pseudoscorpions, entomopathogenic fungi, various bacteria and viruses, kairomones, and benign *V. destructor* haplotypes, as well as structural modifications to hives, such as brood comb modification, rotation, and wire use, are a few of the alternative methods complied and reviewed by Rosenkranz et al. (2010). However, limited results for these hypothesized methods are available, at best, and many of these treatments have never been field tested (Rosenkranz et al. 2010). Some have also suggested that the breeding of *V. destructor* resistant bees is the solution, and this option is currently being explored by researchers, with some positive results; however, this would be a long-term solution and does not solve the issue of colonies that are already infested (Rinderer et al. 2010). Additionally, more recent evidence has suggested that colony size, which is heavily influenced by landscape nutrition, is the best predictor of colony survival (Döke et al. 2019).

IPM Methods

IPM methods have been developed to avoid promoting *V. destructor* resistance, while most effectively using minimal treatments to maintain *A. mellifera* health. An important distinction between IPM and other control methods is that IPM is data driven, using sampling results to guide management practices and thereby keeping *V. destructor* populations below the seasonal economic threshold (Tew 2001). Though biorational acaricides are preferred, synthetic acaricides can still be used, but are rotated to prevent resistance development (Vandervalk et al. 2014). When populations are below the economic threshold (between 2 and 4 mites per 100 bees, depending on the season), they are left untreated, but not unmanaged (Honey Bee Health Coalition 2018).

Cultural and Mechanical Controls

Cultural and mechanical control management methods are recommended before chemical control options, and generally, several of these methods should be combined for greatest efficiency, depending upon the seasonal cycle of the colony (Honey Bee Health Coalition 2018). Basic sanitation practices, such as making sure that hives are well ventilated using screened bottom boards (Calderone 1999), can lead to better hive health and ensure that any mites that fall from their hosts end up outside of the hive (Delaplane et al. 2005). Using distinguishing markings on hives (Honey Bee Health Coalition 2018) and reducing crowding of colonies can also help prevent homing errors, lowering the risks of mite spread between colonies (Seeley and Smith 2015). Culling of older brood frames and drone comb can help reduce both acaricide residue buildup and eliminates more of the drone brood preferred by *V. destructor* (Döke et al. 2015). Breaking the brood cycle by caging the queen or dividing the colony is another way to disrupt mite reproduction, and this method can also be combined with requeening by using a queen selected for mite resistance to facilitate production of stock with more hygienic behaviors (Delaplane et al. 2005). Frequent monitoring is an essential part of keeping mite counts below seasonal thresholds, and results of this monitoring are the best guide in determining which management strategies to pursue (Wantuch and Tarpy 2017).

Many have found IPM strategies to be highly beneficial and consider the development of IPM methods to be the best solution to the *V. destructor* crisis at present, as classical treatment methods have clearly become less effective over the years (Tew 2001, Rinkevich et al. 2017). Another benefit of IPM control methods is that they take into account the individuality of the colonies being treated, allowing for adjustments based on colony size, season, and beekeeper preferences (Honey Bee Health Coalition 2018). IPM methods may also encourage the eventual development of mite resistance by allowing bees to develop natural defenses (Locke 2016).

Concluding Remarks

Over the past 50 yr, *V. destructor* has risen from an obscure pest of *A. cerana* to a near-global epidemic, causing billions of dollars in losses for apiculturists, and severely threatening *A. mellifera* colony survival (Fries et al. 1994, Ahmad et al. 2013). *Varroa destructor* mites are the central cause of colony collapse, which they initiate by parasitizing *A. mellifera* adults and brood, weakening host immunity and spreading viruses (Tantillo et al. 2015). Over the years, control with primarily synthetic acaricides has been attributed to putative resistance development, thus synthetic acaricides have slowly been superseded by organic acids and essential oils, (de Mattos et al. 2017, Vandervalk et al. 2014). This resistance has paved the way for the development of IPM methods, which are expected to help reduce the burden of synthetic acaricides on the bee health, while avoiding *V. destructor* resistance, and potentially aiding in the development of *A mellifera* defenses (Tew 2001, de Mattos et al. 2017). IPM methods are still being developed and tested, but most results thus far have indicated that the future of beekeeping will benefit from the application of IPM practices in *V. destructor* control (Gunes et al. 2017, Honey Bee Health Coalition 2018).

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