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Review Article

The most common predators of *Bemisia tabaci* (Genn.): Biology, predation, preferences, releases, alternative food resources, combined use, current efforts and future perspectives

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ABSTRACT: The cotton whitefly, *Bemisia tabaci* (Genn.) (Hom.:Aleyrodidae) is a serious pest of greenhouses, horticulture and field crops, and ornamentals worldwide. *B. tabaci* has been spreading into new territories and causing extensive damage for almost a century and continues to be a severe pest worldwide. However, resistance to insecticides has rendered chemical control ineffective for the management of *B. tabaci*. Thus, biological control serves as an alternative and has great potential for use against *B. tabaci*. Biological control of *B. tabaci* has been used since more than 40 years, and many attempts have ended with complete success. Biological control of *B. tabaci* by predators represents a key strategy whose potential has gone largely unrealized in many cropping systems. While a great deal of information is available concerning parasitoids of *B. tabaci*, much less is known about potential of predators as bio-agents. Concomitantly, this paper reviews predators' biology, predation, preferences and releases. In addition, combined use of predators and parasitoids, intraguild predation, alternative food resources and omnivory of predators were discussed. In addition, the paper presents the efforts in biological control of *B. tabaci* using selected predators, and highlights research gaps and directions deserving further development to create a better understanding of these predators on different crops to control *B. tabaci*. In spite of hundreds of predators attacking *B. tabaci*, this review is restricted to the most common predators namely; beetles (*Serangium parcesetosum*, *Delphastus catalinae* and *Nephaspis oculatus*), bugs (*Orius laevigatus*, *Macrolophus caliginosus* and *Nesidiocoris tenuis*), lacewings (*Chrysoperla carnea* and *C. pallens*), and mites (*Amblyseius swirskii* and *Euseius ovalis*). In conclusion, based on information presented herein it appears that predators might be best suited for inclusion in multiple species biological control program for *B. tabaci*. It is hoped that this paper will help in better understanding of types of future studies necessary for implementing successful biological control programs.

KEY WORDS: *Bemisia tabaci*, whiteflies, predators, biological control, predation, preferences, alternative food resources, combined use

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BACKGROUND

Bemisia tabaci

The cotton whitefly, *Bemisia tabaci* (Genn.) (Homoptera: Aleyrodidae) is a highly polyphagous pest of more than 600 plant species in tropics and subtropics (Oliveira *et al*., 2001), and temperate regions of the world (Greenberg *et al*., 2000). *Bemisia tabaci* ranks among the most serious pests attacking greenhouse crops (Gerling *et al.,* 2001), horticultural crops (Ko *et al*., 2002), field crops and ornamental plants worldwide (Al-Zyoud and Sengonca, 2004a; Goolsby *et al*., 2005). *Bemisia tabaci* likely came from India, and it is nowadays considered a noxious species in much of the World. *B. tabaci* was firstly classified as a pest in Greece around 1889 and in the USA in 1897 (Brown *et al*., 1995). *Bemisia tabaci* outbreaks in cotton firstly occurred in late 1920s in India, and then in the Sudan and Iran in the 1950s (Horowitz, 1986). In greenhouses, *Bemisia tabaci* was recorded to cause serious damage to vegetables in 1974 in Turkey and to poinsettia in 1986 in the USA (Ohto, 1990). The binomial *B. tabaci* is here used in the broadest sense to include all members of the species complex.

The cotton whitefly causes damage to plants in three ways; firstly by sucking the plant sap, thus weakening plant growth shown by leaf chlorosis, reduction in plant vigor, and general plant stunting (Bedford *et al*., 1994). Physiological disorders caused by direct nymphal feeding include irregular ripening and incompletely development of external color. Secondly, *B. tabaci* secretes large amount of honeydew which enhances the growth of sooty moulds causing negative effect on plant photosynthesis (Abboud and Ahmad, 2006), and this results in less growth, lower yield and poor plant quality (Brown *et al*., 1995), finally lessening the plant market value or yields becoming unmarketable (Giustina *et al*., 1999). Thirdly, *B. tabaci* is considered the most common vector of plant viruses worldwide. More than 150 plant viruses are known to be transmitted by *B. tabaci* and the number continues to grow up (Jones, 2003). Being a vector of hundreds of plant viruses, a small population of *B. tabaci* is sufficient to cause considerable damage to plants. These viral plant diseases have resulted in devastating crop reduction ranging from 20% to 100% throughout plant growing regions in the world with losses estimated at billions of dollars (Giustina *et al*., 1999).

The pest has a high reproductive potential and can reach up to 400 eggs/female. Eggs are laid on the under part of the leaves in groups. After the egg stage, *B. tabaci* hatchling develops through four nymphal instars until it reaches adulthood (Brown *et al*., 1995). The insect has 11-15 generations/year, and the development occurs between 10°C and 32°C, but 27°C appears to be the optimum (Giustina *et al*., 1999).

Biological control

The cotton whitefly has been spreading into new territories, causing severe damage for almost a century and continues to be a serious pest of vegetables and field crops in much of the World (Gerling *et al*., 2001). Farmers depend heavily on the use of insecticides for *B. tabaci* control (Manzano *et al*., 2003; Naveed *et al*., 2011). However, *B. tabaci* population quickly reappears after insecticide applications because immatures are distributed on the underside of plant leaves (Al-Zyoud and Sengonca, 2004a), and are not in contact with insecticides applied through foliar application. In addition, *B. tabaci* has been declared a difficult pest to control by insecticides because of its high mobility, high reproductive rate, and quick life cycle (Drost *et al*., 1998; Gerling and Steinberg, 2003). High doses and frequent pesticide application have adversely affected *B. tabaci* natural enemies (Lacey *et al*., 1993) and human life by increasing pollution as well as disturbed the whole ecosystems (Ashraf *et al*., 2010). Furthermore, reliance on chemical applications for managing *B. tabaci* leads to development of resistance by the pest to many commonly used conventional insecticides (Elbert and Nauen, 2000; Kranthi *et al*., 2001). The resistance of *B. tabaci* to insecticides has rendered chemical control ineffective (Prabhaker *et al*., 1985). Thus, concerns about human health and environment mandate the development of alternatives to chemical control of *B. tabaci*.

There is a growing body of interest in finding control methods for *B. tabaci* other than insecticides, particularly in regions which are unable to sustain heavy pesticide usage (Gerling *et al*., 2001). During the past decades more efforts have been made towards the development of safe alternatives for *B. tabaci* management. Thus, biological control has great potential for use against *B. tabaci* based on the abundance of potential bio-agents (Heinz *et al*., 1999). Biological control is an ecological approach that provides environmentally harmonious, economical pest management, and a safe alternative method for *B. tabaci* suppression (Khan and Wan, 2008a, b). Natural enemies are operating continuously on all life stages of the whitefly, and keep *B. tabaci* populations under control (Goolsby *et al*., 2005). Although biological control alone has not completely been able to solve *B. tabaci* problem in crops, natural enemies still play an important role in IPM programs of agricultural crop (Naranjo and Ellsworth, 2009). Nevertheless, interest in biological control continues to increase worldwide (Castane, 2002) due to the development of pesticide resistance (Elbert and Nauen, 2000; Kranthi *et al*., 2001) and successful use of natural enemies against *B. tabaci* (Stansly *et al*., 2005). Nowadays, research efforts are focusing on controlling *B. tabaci* through mechanisms that do not cause side effects to human and its environment (Al-Zyoud, 2012). Public concern for health risks associated with pesticides is evidenced by the increasing market for organic produce, valued in the USA at $10 billion and in the EU at $13 billion (Dimitri and Oberholtzer, 2005).

Importance of predators

Biological control of *B. tabaci* through the release of natural enemies (parasitoids, predators and pathogens) has been used since more than 40 years, and many attempts have ended with complete success. One biological control mechanism of controlling *B. tabaci* is the use of fungal pathogens. Some species of fungi have been developed as bio-agents against *B. tabaci* (Meekes *et al*., 1996; Chen and Feng, 1999; James and Jaronski, 2000). But, fungi are slow acting compared to insecticides, exhibit poor adulticidal activity, incompatible with many commonly used fungicides, relatively expensive, have limited shelf life, and dependent on favorable environmental conditions (Faria and Wraight, 2001). In addition, development of fungi as bio-agents of *B. tabaci* is still at a fairly early stage, and some strains of whitefly have developed resistance to their fungal pathogens, i.e. *Verticillium lecanii* (Hoddle, 1999).

Other natural enemies of *B. tabaci* are parasitoids, which kill their host once their development has been completed. Extensive listed fauna of parasitoids were used to control *B. tabaci* (DeBarro *et al*., 2000). The best studied and used of these parasitoids are various *Eretmocerus* species (i.e. *Er. mundus* Mercet) (Stansly *et al*., 2005; Urbaneja *et al*., 2007), and many species of the genera *Encarsia* (i.e. *En. formosa* Gahan) (DeBarro *et al*., 2000; Hu *et al*., 2003). Nevertheless, in spite of *B. tabaci* being a host of many parasitoids, it seems that control of this pest by parasitoids is not achieved due to the extensive host range and mobility of the pest (Gerling and Steinberg, 2003). Thus, biological control strategies should include the release of other types of natural enemies.

Predators play a key role in regulating pest populations (Jazzar and Hammad, 2004), and show a great potential in controlling *B. tabaci* than parasitoids and pathogens (Gerling *et al*., 2001). Hundreds of predators have been reported to prey upon *B. tabaci*. The most common predators of *B. tabaci* include ladybird beetles (Coleoptera: Coccinellidae) (Heinz and Parrella, 1994a; Al-Zyoud, 2007, 2008, 2013; Al-Zyoud *et al*., 2007, 2013; Sharma and Joshi, 2010), true bugs (Hemiptera: Anthocoridae and Miridae) (Gerling *et al*., 2001; Calvo *et al*., 2009b), lacewings (Neuroptera: Chrysopidae) (Khan and Wan, 2008a,b), and mites (Acarina: Phytoseiidae) (Nomikou *et al*., 2003b). However, biological control of *B. tabaci* by predators represents a key strategy whose potential has gone largely unrealized in many affected cropping systems throughout the world (Naranjo, 2001). Based on published lists, Gerling *et al.* (2001) catalogued 114 arthropod predators belonging to 9 orders and 31 families. The list has grown up as research progresses. Based on 14 cohorts examined in cotton fields over a three-year-period, predation by sucking predators (i.e. bugs) and chewing ones (i.e. beetles) were responsible for nearly 36% and 31% of all *B. tabaci* immature mortality, respectively (Naranjo, 2001).

Objectives and scope of this review

While a great deal of information is available concerning the impact of parasitoids on *B. tabaci*, much less is known about predators' potential as bio-agents. Additionally, adult *B. tabaci* and their predators are highly mobile; as a consequence, direct field observations of *B. tabaci* predation are tedious and time consuming (Hagler *et al*., 2004). Concomitantly, this paper reviews predators' biology, predation potential and prey preferences. In addition, predators' releases against *B. tabaci* are herein presented. Furthermore, combined use of predators and parasitoids and intraguild predation are discussed. Since, alternative food resources and omnivory of *B. tabaci* predators facilitate the setup of mass rearing which can promote their persistence in the crop, even in the absence of prey, they are also considered in this study. Finally, this review summarizes the efforts in biological control of *B. tabaci* using selected predators during the last decades, and also highlights research gaps and directions deserving further development to create a better understanding of these predators in controlling *B. tabaci* on different agricultural crops. It is hoped that this paper will help in a better understanding of the types of studies necessary for implementing future programs and perspectives. In spite of hundreds of predators attacking *B. tabaci*, this review is restricted to the most common predators belonging to four major groups of arthropods namely; ladybird beetles, true bugs, lacewings and mites.

PREDATORS

Lady beetles (Coleoptera: Coccinellidae)

The coccinellids, *Serangium parcesetosum* Sicard, *Delphastus catalinae* (Horn) and *Nephaspis oculatus* (Blatchley) are herein thoroughly discussed. The predaceous insects of family Coccinellidae are commonly known as ladybirds, ladybugs, lady beetles or coccinellid beetles (Sharma and Joshi, 2010). Coccinellids have worldwide distribution (Almeida *et al*., 2011), and widely used in biological control for more than a century. Ladybirds are of extremely diverse habits, predators of a variety of pests such as whiteflies, aphids, leafhoppers, scale insects, mealybugs, thrips and mites worldwide (Omkar and Bind, 1996; Al-Zyoud, 2012, 2013). Predaceous coccinellids are more linked to biological control than any other taxa of predatory arthropods (Obrycki and Kring, 1998). *Bemisia tabaci* are preyed upon by many coccinellid species, which are considered important predators of whiteflies in general and may exhibit various degrees of oligophagy (Obrycki and Kring, 1998).

The predator, *S. parcesetosum* is a specialist, oligophagous and efficient predator that has demonstrated a potential for the biological control of many whitefly species, and has been thoroughly investigated on *B. tabaci* during the past decade (Ellis *et al*., 2001; Al-Zyoud and Sengonca, 2004b; Al-Zyoud *et al*., 2004, 2005b, 2006, 2007, 2013; Al-Zyoud, 2007, 2008, 2012, 2013). *S. parcesetosum* was firstly observed in India and reported there to be a very specific to *B. tabaci* (Kapadia and Puri, 1992a). Hereafter, the predator has been thoroughly investigated against other whitefly species, where it was found also feeding on the citrus whitefly, *Dialeurodes citri* (Ashmead) (Timofeyeva and Nhuan, 1979; Malausa *et al*., 1988; Ahmad and Abboud, 2001; Yigit *et al*., 2003), the sugarcane whitefly, *Aleurolobus barodensis* Mask**.** (Kapadia and Butani, 1997), the greenhouse whitefly, *Trialeurodes vaporariorum* (Westwood) (Al-Zyoud *et al*., 2005a), the castor bean whitefly, *Trialeurodes ricini* (Misra) (Al-Zyoud, 2007), the spiraling whitefly, *Aleurodicus dispersus* Russell, and the arecanut whitefly, *Aleurocanthus arecae* David and Manjunatha (Legaspi *et al*., 1996).

The ladybird, *D. catalinae* is also an obligate and promising predator of whiteflies (Simmons and Legaspi, 2004; Simmons *et al*., 2008), especially under greenhouse conditions (Liu, 2005). Although this predator is native to South America, established populations are also found in several tropical and subtropical regions (Gordon, 1994). Several studies have demonstrated its potential for *B. tabaci* control (Hoelmer *et al*., 1994; Liu and Stansly, 1999). Results from a comparison among 14 species of parasitoids and predators suggested that *D. catalinae* may be a superior biological control agent for *B. tabaci* (Heinz, 1996).

D. catalinae has been extensively studied as a bio-agent for many whitefly species such as *Aleurocanthus woglumi* Ashby, *Pealius kelloggi* (Bemis), *Trialeurodes floridensis* (Quaintance) and *D. citri* on citrus in USA (Smith and Maltby, 1994), and *Trialeurodes variabilis* (Quaintance) on cassava in Colombia (Gold *et al*., 1989).

The beetle, *N. oculatus* is a native coccinellid of Central America, and has been well established in Florida (Gordon, 1985). It was first reported preying upon *B. tabaci* in Florida (Hoelmer *et al*., 1994). *N. oculatus* is a predator of whiteflies, and shows good potential for biological control, especially in greenhouses (Liu *et al*., 1997). The biological control potential of *N. oculatus* was recognized due to its capacity to consume large numbers of *B. tabaci*, and it's proven ability to control the pest on cotton and greenhouse-grown ornamental plants in the USA (Heinz and Parrella, 1994a; Hoelmer *et al*., 1994). *N. oculatus* has been reported preying on other whitefly species, including *A. woglumi*, *P. kelloggi*, *T. floridensis*, *D. citri* and *D. citrifolii* (Morgan) (Gordon, 1985), *A. dispersus* (Yoshida and Mau, 1985).

Long survival of *S. parcesetosum* adults (Sengonca *et al*., 2004) accomplished by voracious feeding (Sengonca *et al*., 2005) is a great feature that results in a successful control of *B. tabaci* (Ellis *et al*., 2001; Al-Zyoud, 2008). Longevity of 6 months for *S. parcesetosum* was reported on cotton infested by *B. tabaci* (Sengonca *et al*., 2004). The ability of a predator to oviposit successfully on the host plant on which its prey lives is one of the major factors in determining its ability to successfully control the pest. *S. parcesetosum* has a high fecundity of 444 eggs/female on cabbage at 27°C (Ahmad and Abboud, 2001) and 355 eggs/female on cotton at 25°C when fed on *B. tabaci* (Vatanesever *et al*., 2003). The fecundity is 3-fold higher when *S. parcesetosum* fed on *B. tabaci* (Sengonca *et al*., 2004) than on *T. vaporariorum* (Al-Zyoud *et al*., 2005a). With regards to *D. catalinae* feeding on *B. tabaci*, adult longevity of 5 months and a fecundity of 325 eggs/female were reported (Liu, 2005). Adult longevity of 4.5, 4.0 and 2.5 months and fecundity of 243, 258 and 104 eggs/female were stated at 22, 26ºC and 30ºC, respectively (Legaspi *et al*., 2008). Adult longevity of 3 months at 27ºC (Heinz and Parrella, 1994b), 3.5 months at 25°C (Simmons and Legaspi, 2004), and 6 months at 25ºC (Simmons and Legaspi, 2004) of *D. catalinae* combined on *B. tabaci* were also recorded. *N. oculatus* adult longevity averaged 2 months, and females laid a mean of 3 eggs/day (Liu *et al*., 1997).

A successful biological control of a pest species depends on the fact that the predator destroys, kills or consumes sufficient number of the pest to keep its population below the economic threshold level (Sengonca *et al*., 2005). *S. parcesetosum* larvae can consume up 310 *B. tabaci* immatures/day at 25°C on cucumber (Al-Zyoud, 2008) and 235 nymphs or 36 pupae (Sengonca *et al*., 2005). During its entire larval development, *S. parcesetosum* consumes 1,566 nymphs or 280 pupae at 18°C, 1,119 nymphs or 188 pupae (Sengonca *et al*., 2005), 1,542 immatures (Al-Zyoud, 2008), 1,678 eggs or 195 pupae (Ahmad and Abboud, 2001), and 1,055 nymphs of *B. tabaci* (Asiimwe *et al*., 2007). *S. parcesetosum* adults feed daily on 74 nymphs or 40 pupae (Sengonca *et al*., 2005), 144 immatures (Al-Zyoud, 2008), 271 eggs or 23 pupae of *B. tabaci* (Ahmad and Abboud, 2001). While on over 60 days of longevity, *S. parcesetosum* adults consumed 3,948 nymphs or 1,601 pupae of *B. tabaci* (Sengonca *et al*., 2005), on over 80 days of longevity, it consumed around 7,800 *B. tabaci* immatures (Al-Zyoud, 2008). The maximum cumulative lifetime predation was measured at more than 10,000 *B. tabaci* (Legaspi *et al*., 1996). With regard to *D. catalinae*, 4th instar consumed daily 167 eggs or 12 nymphs of *B. tabaci* (Liu, 2005). In contrast, daily and total consumptions were 79, 86 and 373 eggs as well as 748, 730 and 765 eggs of *B. tabaci* by *N. oculatus* males, females and larvae, respectively (Liu *et al*., 1997).

The prey's population available in the agro-ecosystem for a natural enemy will never be constant and it fluctuates in relation to many factors. To be considered as an efficient natural enemy, a predator is expected to be able to adapt itself to fluctuation in prey availability. *S. parcesetosum* adapted itself smoothly to *B. tabaci* fluctuation (Sengonca *et al*., 2005), and it imposed positive density dependence with *B. tabaci* (Al-Zyoud *et al*., 2013). Predators having such a type of response allow long-term population persistence (Pech *et al*., 1992), and in turn will effectively stabilize their prey population. Hoelmer *et al*. (1993) reported that *D. catalinae* would probably not persist with low whitefly populations, and its capacity to feed on alternative foods like spider mites (Hoelmer *et al*., 1993) may be crucial for its survival. The apparently more efficient search behavior of *N. oculatus* might impart a further advantage under conditions of relatively low prey density (Liu and Stansly, 1999).

Before considering a predator in biological control, it is important to investigate its affinity toward a certain developmental stage of the target pest or even the pest species to be controlled. This is true especially when taken into account that under greenhouses and open field conditions there are naturally several pest species that might serve as potential prey for the predator. Investigating the preferred prey stage would be useful in determining which developmental stage of the prey is the most predated, and this will facilitate its mass rearing, which is a prime objective in biological control (Sahayaraj and Paulraj, 2001). Predators are known to display different prey-preference responses when presented with various life stages of a prey. *S. parcesetosum* prefers puparia and nymphs than eggs of *B. tabaci* (Al-Zyoud and Sengonca, 2004b). In contrast, *D. catalinae* and *N. oculatus* consumed more eggs than other immature stages (Hoelmer *et al*., 1993; Liu *et al*., 1997). All the three predators could feed on all *B. tabaci* developmental stages (Hoelmer *et al*., 1993; Ahmad and Abboud, 2001), and they are relatively slow runners, which could enhance their ability to control whiteflies (Liu and Stansly, 1999). *S. parcesetosum* preferred significantly the whitefly species used (*B. tabaci*, *T. vaporariorum* and *T. ricini*) consuming very few individuals from aphids (*Aphis gossypii* Glover), thrips (*Frankliniella occidentalis* Pergande), mites (*Tetranychus urticae* Koch) and pea leafminer (*Liriomyza huidobrensis* Blanchard) (Al-Zyoud and Sengonca, 2004b; Al-Zyoud, 2007). In addition, *S. parcesetosum* prefers *B. tabaci* more than *T. vaporariorum* (Al-Zyoud, 2007), *D. citri* and the woolly whitefly, *Aleurothrixus floccosus* (Maskell) (Abboud and Ahmad, 1998), and *A. woglumi* (Legaspi *et al*., 2001).

A single release of one *S. parcesetosum* adult/plant caused a reduction in *B. tabaci* population by 65% and 62% (1 predator: 30 whiteflies), 62% and 60% (1: 20) on cucumber plants, and 89% and 82% (1: 25) on cotton plants when the predator was introduced 1 and 2 weeks after *B. tabaci* infestation, respectively (Al-Zyoud *et al*., 2007; Al-Zyoud, 2013). *B. tabaci* population in cages receiving 2 and 4 *S. arcesetosum* adults/plant showed 56% and 53% reductions on eggplants, respectively (Kutuk *et al*., 2008). Ellis *et al*. (2001) stated that introduction of *S. parcesetosum* was extremely effective at stopping the growth of *B. tabaci* population on poinsettias under greenhouse conditions for 10 weeks. In exclusion caged experiments, releases of 3-5 *D. catalinae* adults/plant caused 55% and 67% decrease in densities of *B. tabaci* in two different seasons in the field (Heinz *et al*., 1999). Early season releases of *D. catalinae* and *S. parcesetosum* may suppress whitefly populations before they reach uncontrollable levels (Heinz *et al*., 1999; Al-Zyoud *et al*., 2007).

True bugs (Hemiptera: Anthocoridae and Miridae)

The anthocorid bug, *Orius laevigatus* (Fiber) and the mirid bugs, *Macrolophus caliginosus* Wagner and *Nesidiocoris tenuis* (Reuter) are here discussed. Hemiptera are usually polyphagous and prey specificity is rare (Fauvel, 1999), and they are predators of aphids (Alvarado *et al*., 1997), thrips (Riudavets and Castane, 1998), and mites (Venzon *et al*., 2002). Several hemipterans are frequent generalist predators of *B. tabaci* and can contribute to the control of the pest (Arno *et al*., 2008; Calvo *et al*., 2009b).

The predator, *O. laevigatus* is the most used in Europe (Shipp and Ramakers, 2004), and both nymphs and adults were able to feed on eggs and nymphs of *B. tabaci*. The preference for feeding on eggs was higher than the nymphs. During the 17 days of larval development, *O. laevigatus* consumed 365 immatures. The adult longevity of *O. laevigatus* was about 22-26 and 14-15 days, and during adulthood, the predator consumed 883 and 455 *B. tabaci* immatures with a daily consumption of 27 and 19 immatures on tomato and eggplant, respectively (Hamdan and Abu-Awad, 2008). The mirid bug, *M. caliginosus* is a zoophytophagous predator found on numerous plants in both fields and greenhouses in the Mediterranean basin (Alomar *et al*., 1994). It is currently commercialized in Europe for the control of *B. tabaci* (Alomar *et al*., 2003; Jazzar and Hammad, 2004) in greenhouses. *O. laevigatus* showed higher voracity of predation on *B. tabaci* than thrips (Tommasini *et al*., 2004). *M. caliginosus* showed a preference for *B. tabaci* nymphs than eggs (Bonato *et al*., 2006). Immature *M. caliginosus* consumed daily a mean of 23 eggs and 24 mature nymphs of *B. tabaci*, respectively (Bonato *et al*., 2006).

The European species, *N. tenuis* is widely used for augmentative biological control of *B. tabaci*. Effective control of *B. tabaci* by *N. tenuis* was demonstrated in large cage studies (Calvo *et al*., 2008, 2009b). However, trials in experimental and commercial greenhouses were less successful (Nannini, 2001) and high release rates were required for satisfactory control. Best results were obtained when releases were made early during the season and/or reinforced with releases of *En. formosa*. Whitefly reductions of up 81% and 96% were recorded with only one release of 1 or 4 *N. tenuis*/plant, respectively. *N. tenuis* established well in the tomato crop under the experimental conditions. However, *N. tenuis* is also considered a pest because it can feed on plants, causing necrotic rings on stems and flowers and punctures in fruits. The necrotic rings were observed with the greatest incidence always in cages receiving 4 *N. tenuis*/plant (Calvo *et al*., 2009b). But, it is to be mentioned that *N. tenuis* does not develop successfully on tomato plants without prey (Urbaneja *et al*., 2005). It seems that *N. tenuis* feeds on tomato plants when there is a lack of prey. To avoid undue injury to a tomato crop by *N. tenuis*, special attention should be paid to the release ratio (Lucas and Alomar, 2002). Urbaneja *et al*. (2005) showed that on tomato *N. tenuis* was able to complete its life cycle in 13, 21 and 23 days feeding on *B. tabaci*, *F. occidentalis* and *T. urticae*, respectively. Thus, the presence of these other pests could potentially increase the tolerance level for *N. tenuis* per plant without significant increase in plant damage. Establishment of predatory bugs is generally slow and all feed on plants when prey is scarce (Calvo *et al*., 2008, 2009b). Shipp and Wang (2006) reported that increase in release rate of the predatory bugs will lead to crop damage, and insecticidal control against predatory bugs is required when it exceeded 4/plant and adult whitefly were less than

20/plant. As a consequence, the status of a mirid species as a pest or biological control agent will depend on crop, pest complex, and possibly other circumstances.

Lacewings (Neuroptera: Chrysopidae)

Chrysopids are polyphagous predators that suppress the population of many pest species, i.e. aphids (Jokar and Zarabi, 2012), mites (Hagley and Miles, 1987), scale insects (Miller *et al*., 2004), and thrips (Herold and Stengel, 1994). In addition, chrysopids prey upon whiteflies (Jokar and Zarabi, 2012).

The predator, *Chrysoperla carnea* (Stephens) is a common polyphagous species with voracious feeding habit (Kareim, 1998), and it has got a considerable attention as a biological control agent because of its ability to control a variety of insect pests, wide adaptability in field than other predators (Gautam and Tesfaye, 2002), its compatibility with a variety of food diversity and ability to prey on 80 pest species (Jokar and Zarabi, 2012). *C. carnea* larvae feed on all immature stages of whiteflies (Jokar and Zarabi, 2012). Gerling *et al*. (1997) reported that population of *C. carnea* and *B. tabaci* in cotton fields occurred together and the predator larvae fed on *B. tabaci* nymphs. But, *C. carnea* was not an efficient predator and it is probably related to behavioral preferences of the predator as well as to its nutritional demands that were met only marginally by feeding on whiteflies. Balasubramani and Swamiappan (1994) reported that the development of *C. carnea* was faster on *B. tabaci* than on *A. gossypii*. In contrast, Kapadia and Puri (1992b) observed that *C. carnea* preferred aphids to whiteflies. The preference of aphids over *B. tabaci* corresponds also to observations that *B. tabaci* nymphs constitute a poor diet for non-specialized predators such as *C. carnea*, especially because of their low methionine levels. Nevertheless, *C. carnea* has been mass-reared and marketed commercially in North America and Europe (Tauber *et al*., 2000; Gautam and Tesfaye, 2002). *C. carnea* efficiency increased with increasing prey density (Syed *et al*., 2005). The entire larval period took an average of 14 days when fed on *B. tabaci* (Jokar and Zarabi, 2012). The number of *B. tabaci* consumed by *C. carnea* larvae is around 25/day or 500 during their 20-day period of larval development (Gerling *et al*., 1997; Gautam and Tasfaye, 2002). *C. carnea* contributes to whitefly suppression and could prevent the outbreaks during low whitefly populations, and it caused a reduction of 57% in *B. tabaci* population in cotton fields (Zia *et al*., 2008). Although *C. carnea* occurs throughout cotton fields, and it can consume *B. tabaci* immatures, nutritional deficiency, the number of whitefly nymphs consumed per day, and the preference for other prey may play an important role in reducing its importance as a predator of *B. tabaci* (Gerling *et al*., 1997). Mohyuddin *et al*. (1997) reported that biological control is the paramount alternative for controlling *B. tabaci* by the augmentation of *C. carnea*. Khuram *et al*. (2008) showed that use of *C. carnea* as bio-agent of *B. tabaci* reduced the usage of insecticides on cotton.

Chrysopa pallens (Rampur) was also able to develop and reach adult stage when fed on *B. tabaci,* with the developmental duration of 38 days (Khan and Wan, 2008b). The longevity of *C. pallens* was 1.5-2 months with total fecundity of 397 eggs/female (Khan and Wan, 2008b). Jagadish and Jayaramaiah (2004) stated longevity of *C. carnea* of 1 month with total fecundity of 385 eggs/females. The predatory capacity of *C. pallens* feeding on *B. tabaci* increased with increasing prey density. *B. tabaci* pupae are the favorite prey of *C. pallens* (Liu *et al*., 2011).

Predatory mites (Acari.: Phytoseiidae)

Phytoseiid mites are actively predaceous upon mites, thrips, aphids and scale insects (McMurtry and Croft, 1997; El-Banhawy *et al*., 2000). In addition, mites of the family Phytoseiidae are well known predators of whiteflies (Nomikou *et al*., 2001a; Hagler *et al*., 2004). Many phytoseiid species have also been reported to feed on pollens as alternative food, so that certain plant pollens have been used for mass-rearing of several phytoseiids for field release (Madnneli *et al*., 2002). Furthermore, predatory mites are generalist predators that are known to feed also on honeydew and plant juice (Abdallah *et al*., 2001). The predator, *Amblyseuys swirskii* (Athias-Henriot)*i* is a very popular species, because it not only controls thrips (Messelink *et al*., 2006), but also whiteflies (Nomikou *et al*., 2001b; Calvo *et al*., 2009a), and mites (Messelink *et al*., 2010). The phytoseiid, *Euseius ovalis* (Evans) is a predator of thrips and whiteflies (Manjunatha *et al*., 2001; Messelink *et al*., 2008).

Amblyeius swirskii appears to be a promising biological control agent against *B. tabaci* (Nomikou *et al*., 2001a; Hagler *et al*., 2004). According to Kandeel *et al.* (1994), *A. swirskii* life cycle was completed in 7 days on *B. tabaci*, and consumes 312 immatures during this period. *A. swirskii* was collected in Israel in association with *B. tabaci* and tested as a bio-agent for the pest, and the predator has shown a high efficacy against *B. tabaci*. In greenhouse cucumber, *B. tabaci* control by *A. swirskii* and *E. ovalis* was not sufficient in the absence of thrips, but the densities were dramatically reduced in the presence of thrips (Messelink *et al*., 2008). Nowadays, *A. swirskii* is increasingly used for biological control of whiteflies in many crops. Biological control strategies in crops might be improved by tolerating acceptable levels of both thrips and whiteflies in order to stimulate population growth of predatory mites (Messelink *et al*., 2008). In the absence of *A. swirskii*, *B. tabaci* populations increased exponentially over a period of two months, whereas their growth was much slower in the presence of *A. swirskii*. The number of predators per plant was higher on plants with pollen, than on pollen-free plants. Control of whiteflies with *A. swirskii* on cucumber was much better when pollen was added, because of the higher number of predators on leaves with pollen (Nomikou, 2003). However, the developmental period of predatory mites in general is about 1 week and adult longevity is less than 1 month, which is shorter comparing to other types of *B. tabaci* predators.

The most recent breakthrough in whitefly biological control has been the development and commercialization of *A. swirskii* (Calvo *et al*., 2008, 2009b). Nomikou *et al*. (2001b) showed that populations of *B. tabaci* were reduced 16- to 21-fold on cucumber plants receiving *A. swirskii* compared to those that did not. Whitefly populations in the presence of *A. swirskii* were suppressed at levels more than 40-fold lower than in the control (Nomikou *et al*., 2003c). *A. swirskii* provided better control of *B. tabaci* than the use of insecticides on eggplant (Stansly and Castillo, 2009). The ability to feed on alternate hosts is a distinct advantage and significant suppression of *B. tabaci*. The mites also feed on pollen and therefore could be released preventively before *B. tabaci* are present (Nomikou *et al*., 2003c).

ALTERNATIVE FOOD RESOURCES AND OMNIVORY OF *BEMISIA TABACI* PREDATORS

The ability of a predator to survive on alternative nutritional sources has an advantage in stabilizing its population dynamics (Lalonde *et al*., 1999). However, a major stumbling block to the use of biological control on a large scale is that it has been difficult to produce adequate numbers of predatory insects to make a significant reduction of *B. tabaci* population. For example, predators have been used successfully for a decade to control *B. tabaci*; however, the scale of their use has been limited because of inadequate methods to artificially produce these predatory insects. Predators can utilize a variety of food sources from their habitat such as plant-produced pollen, nectar, fruits, leaf tissue and honeydew produced by homopteran insects such as *B. tabaci* (van Rijn and Tanigoshi, 1999; Nomikou *et al*., 2010).

In case of *S. parcesetosum,* a growth medium composed of a mixture of an adherent and fibrous retention substrate, a protein-lipid paste, and a liquid was successfully used to rear the predator for three generations (Hodek and Honek, 2009). The predatory bug, *O. laevigatus* can easily be reared on frozen eggs of the flour moth (Tommasini *et al*., 2004). *D. catalinae* and *N. oculatus* larvae fed on honeydew even when abundant whiteflies were available. Availability of alternate food might allow the coccinellids to survive periods of low *B. tabaci* density (Liu and Stansly, 1999). Many predatory mites are generalist predators and use non-prey food sources such as pollen, nectar and honeydew (McMurtry and Croft, 1997). Utilization of non-prey food sources by phytoseiids is significant for biological control since it allows predators' populations to persist in the crop in periods that prey is scarce or absent (van Rijn *et al*., 2002). Both pollen and honeydew could play an important role in the biological control of *B. tabaci* because these non-prey food sources affect positively life history parameters of predatory mites, and maintain their effectiveness against *B. tabaci* throughout the crop-growing season (Nomikou *et al*., 2003a). Pollen of several plant species is suitable for growth and reproduction of various predators and it is frequently used for mass rearing of predatory mites (van Rijn and Tanigoshi 1999). The addition of pollen to plants with predators led to a more than 8-fold extra reduction of *B. tabaci* populations, and *A. swirskii* reached higher numbers on plants with pollen (Nomikou *et al*., 2003c).

Predators that feed on both animals and plants are a particular case of trophic omnivory (Coll and Guershon, 2002). Plant-feeding omnivores can stabilize the dynamics and persistence of populations by switching between consuming plants and prey (Lalonde *et al*., 1999). Many predators that are used for biological control are true omnivores, feeding on pests and plant-provided food such as pollen, nectar and plant saps. For example, many generalist predatory mites and bugs can complete their life cycle feeding on pollen. Not all greenhouse crops produce pollen, but some omnivores, such as predatory bugs can also live and reproduce on plant saps. The consumption of prey in addition to plant material by mired bugs can increase reproduction rate and increased survival (Perdikis and Lykouressis, 2004). While facultative herbivory is common among many predaceous true bugs (Rosenheim *et al*., 1995), it is surprising that a greater research effort has not been made towards determining what advantages in fitness are derived by predators that feed on plants. Hence, the use of alternative food for predators in biological control programs may improve the success of *B. tabaci* control (van Rijn *et al*., 2002).

COMBINED USE OF PREDATORS AND PARASITOIDS AND INTRAGUILD PREDATION

Before considering a predator in a biological control program, it is important to investigate its possible interaction with other natural enemies. This is true especially when taken into account that under greenhouses and open field conditions there are several natural enemies that could interact with the released predator. Parasitoid species belonging to the genera *Eretmocerus* and *Encarsia* are commonly used to control *B. tabaci* (Abd-Rabou, 1999). Efficiency of a predator in biological control depends among many other factors on its possible interaction with other predators in the agro-ecosystem, and its ability to avoid feeding on parasitized *B. tabaci*.

The predator, *S. parcesetosum* tends to avoid parasitized *B. tabaci* by *En. formosa* (Al-Zyoud and Sengonca, 2004b) and *Er. mundus* (Al-Zyoud, 2007) feeding on unparasitized pupae. In addition, *D. catalinae* differentiates between unparasitized *B. tabaci* and those parasitized with *En. transvena* (Timberlake) (Hoelmer *et al*., 1994) and *En. sophia* (Girault and Dodd) (Zang and Liu, 2007). When *En. formosa* and *S. parcesetosum* released to control *B. tabaci* on poinsettias, *B. tabaci* densities in the greenhouse area receiving both natural enemies were less than those receiving each one alone (Weaver and Ciomperlik, 2000). Greater and enhanced control of *B. tabaci* may be achieved by using *D. catalinae* in conjunction with *En. luteola* Howard (Heinz and Parrella, 1994a, b), *En. formosa* and *En. pergandiella* Howard (Heinz and Nelson, 1996). Releases of *D. catalinae* did not adversely affect population densities of indigenous parasitoids, suggesting an absence of antagonistic predator-parasitoid interactions (Heinz *et al*., 1999). Zapata *et al*. (2003) mentioned that release of *Er. mundus* in combination with *M. caliginosus* provides a great level of whitefly suppression. Because *M. caliginosus* often has an establishment time of about 1 month, *En. formosa* can be released to provide more immediate whitefly suppression (Muhlberger and Maignet, 1999). Release of *Er. eremicus* Rose and Zol-Nerowich with *O. laevigatus* have suppressed the whitefly population. *C. pallens* consumed higher number of un-parasitized *B. tabaci* by *En. formosa* than parasitized ones (Khan and Wan, 2008a). Calvo *et al*. (2008) reported that the best biological control strategy for *B. tabaci* on eggplant was the combination of *A. swirskii* and *Er. mundus*. Studies concluded that predators avoid or are unable to feed on parasitized *B. tabaci* in advanced stages of development. Thus, because the parasitized whiteflies by *En. formosa* and *Er. mundus* are currently in use worldwide to control *B. tabaci* (Abd-Rabou, 1999) from one hand, and from the other hand these parasitoids are avoided by many predators, there is a feasible potential for integration of predators and parasitoids into *B. tabaci* management programs in order to provide a great level of pest suppression, and this will lead to widespread adoption of biological control of the pest.

Natural enemies can compete for the same prey species, but this is frequently combined with predation by one species of natural enemy upon another “intraguild predation” (Rosenheim *et al*., 1995). However, it has become clear that intraguild predation generally occurs in many ecosystems including biological control systems (Janssen *et al*., 2007). The effects of intraguild predation on disruption of biological control are poorly understood in most systems (Naranjo, 2001). Intraguild predation results in less effective biological control (Rosenheim, 2005). Jakobsen *et al*. (2004) reported that nymphal stages of *M. pygmaeus* Rambur are vulnerable for predation by *O. majusculus* (Reuter). Predatory bugs of the genus *Orius* act as intraguild predators of phytoseiid mites (Chow *et al*., 2008). Many generalist predatory mites are intraguild predators of other predatory mites (Buitenhuis *et al*., 2010) or nymphal stages of predatory bugs. *Orius* spp. feeding on eggs of *D. catalinae* and *Chrysoperla sp*. These direct field observations suggested that predator mortality by indigenous predators may have been significant, especially in the open fields. These negative predator-predator interactions may have reduced greatly the ability of *D. catalinae* releases to effect biological whitefly control (Heinz *et al*., 1999). Intraguild predation is usually more intense when prey density is low, and it has been identified as one of the main factors affecting efficiency of predators and consequently the success of biological control programs (Rosenheim, 1998). The future biological control program based on releasing predators should focus on intraguild predation.

CONCLUSIONS

The selected coccinellid predators in this study (*S. parcesetosum*, *D. catalinae* and *N. oculatus*) are characterized by their specificity and oligophagy on whiteflies i.e. *B. tabaci*. In contrast, the predatory bugs (*O. laevigatus*, *M. caliginosus* and *N. tenuis*), lacewings (*C. carnea* and *C. pallens*) and mites (*A. swirskii* and *E. ovalis*) are usually polyphagous and lack prey specificity predating, in addition to *B. tabaci*, on aphids, thrips, spider mites and scale insects. It is to be mentioned that *B. tabaci* constitutes a poor diet for polyphagous predators larvae, especially because of their low methionine levels.

Comparing with all other predators, coccinellid predators have long survival period (up to 6 months for *S. parcesetosum* and *D. catalinae*), and high fecundity (444 eggs/female for *S. parcesetosum* and 325 eggs/female for *D. catalinae*). In addition, the coccinellid predators show a very high predation potential, i.e. *S. parcesetosum* larvae consume 310 *B. tabaci* immatures/day, and a total of 1,566 nymphs, and over 80 days of longevity, the predatory adults consume more than 7,800 *B. tabaci*, and can reach up to 10,000 *B. tabaci*), while the predatory bug, *O. laevigatus* larvae and adults consume in total 365 and 883 immatures, respectively, with a daily consumption of 27 immatures. Also the whitefly immatures consumed by *C. carnea* larvae do not exceed 25/day or 500 during their larval development, and predatory mite, *A. swirskii* larvae feed on only 312 immatures. Thus, coccinellids have a great future to be used as predators for the successful control of *B. tabaci*.

A single release of coccinellid predators caused a significant reduction in *B. tabaci* population by 89%, and early season releases of the predators suppress whitefly populations better than late releases before they reach uncontrollable levels. In contrast, to be effective, the predatory bugs should be released at a high rate per plant, but their high number can also cause them to feed on plants. Thus, to avoid phytophagy by predatory bugs, special attention should be paid to the release rate. The lacewing predators generally consume low number of whitefly daily, and their preference for other prey may play an important role in reducing its importance as a predator of *B. tabaci*. The predatory mites can control *B. tabaci* if other pests or pollen are available on the crop and this will help to stimulate population growth of predatory mites.

In order to use biological control on a large scale, alternative nutritional sources of predators should be taken into account. Predators can utilize a variety of food sources from their habitat such as pollen, nectar, fruits, leaf tissue and honeydew produced by *B. tabaci*. Utilization of non-prey food sources by predators is a positive feature for biological control since it allows populations of predators to persist on the crop during periods of prey scarcity or absence. Also, when prey is present the addition of pollen to plants with predators led to enhanced reduction in the whitefly populations. In addition, plant-feeding predators (predatory mites and bugs) can stabilize the persistence of populations by switching between consuming plants and prey. Food sources other than *B. tabaci* can increase survival and reproduction rates, affect life history of predators, improve population persistence, and maintain their effectiveness against *B. tabaci*. Hence, the use of alternative food for predators in biological control programs may improve the success of pest control.

Apart from other factors efficiency of a predator in biological control depends on its possible interaction with other natural enemies in the agro-ecosystem, and its ability to avoid feeding on parasitized *B. tabaci*. However, all the predators investigated in this study tend to avoid feeding on parasitized *B. tabaci*. In addition, all studies indicated that when a combination of predator and parasitoid were released against *B. tabaci*, the whitefly densities receiving both natural enemies were less than those receiving each one alone. Thus, because *En. formosa* and *Er. mundus* are currently in use worldwide to control *B. tabaci* but the concern is that parasitized hosts are avoided by many predators, hence there is a feasible potential for integration of predators and parasitoids into *B. tabaci* management programs in order to provide a greater level of pest suppression, and this will lead to widespread adoption of biological control worldwide. Intraguild predation generally occurs in biological control systems, and it is usually more intense when prey density is low, and it has been identified as one of the main factors affecting the success of biological control programs. Thus, the effect of intraguild predation on disruption of biological control is still poorly understood in most systems, and more researches should be done on this topic.

The use of generalist predators were long considered as less effective than specialist ones. However, several studies indicate that generalist predators can be effective bioagents, especially because their populations can be easily established since they feed on many pests (Messelink *et al*., 2010). In contrast, releases of specialist predators often involve problems with timing, and quality of control. Generalist predators can establish into crops prior to pest infestations, which makes the system resilient to pest invasions. Thus, future research should focus on establishment of generalist predators by offering alternative prey on banker plant systems, or by selecting plants that provide food, nectar, pollen or shelter. Also, more attention should be paid on research focusing on selecting the predators that are well adapted to the crops and perform well on the pests rather than selecting predators depending only on the pest species. In addition, predator feeding behavioral studies should be conducted to be combined with studies of preferences and predation potential to determine the predatory potential for *B. tabaci* biological control.

The use of insecticides against *B. tabaci* will be less effective due to the resistance of the pest to chemicals. Whiteflies, mites and aphids have shown resistance to more that 100 insecticides and this number is expected to grow up. Thus, with progress of time it is expected that these insects including *B. tabaci* will resist all chemical insecticides and use of alternative methods is a must and biological control will be one of the most available and promising alternative to control pests. Finally, biological control of *B. tabaci* will remain a challenge in many crops, thus it is hoped that this review will help in better understanding of types of future studies necessary for implementing successful biological control programs of *B. tabaci*.

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