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Beneficial insect community of Moroccan citrus groves: assessment of their potential to enhance biocontrol services

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Abstract

In citrus groves, beneficial insects that reduce abundance of pests are considered a key component of integrated pest management strategies. The aim of this article was to assess the biodiversity of parasitoids and predators in citrus orchards in Moroccoto facilitate future investigations on their potential as biocontrol agents. Data of 105 citrus beneficial insects were gathered and summarized in a data matrix. Variables such nature, target pests, type, establishment, and efficacy were assessed. More than two-thirds of parasitoids and predators species identified in citrus groves of Morocco (105 species) are native (> 70%). Both groups represent only a small fraction of the introduced species. The mostly attack armored scale insects (Diaspididae) and aphids (Aphididae). The ladybeetle *Rodolia cardinalis* (Mulsant) (Coleoptera: Coccinellidae) is the first beneficial species introduced in 1921 to the Moroccan citrus orchards to control the cottony cushion scale *Icerya purchasi* (Maskell) (Hemiptera: Monophlebidae). Major introductions of these parasitoids and predators were carried out during the ninetieth to control the main citrus pests whereas they were accidentally introduced. These purposely introduced species are mainly Aphelinidae, Encyrtidae, Eulophidae, Coccinellidae, and Phytoseiidae. Whereas a high proportion of the introduced beneficial insects was established and no species have been reported to be harmful to this date. Considering only the introduced species used in classical biological control context, about 20 and 40% of them are considered as effective or partially effective, respectively.

Keywords: Citrus, Biological control, Parasitoids, Predators, Species diversity, Morocco

Background

In Morocco, the citrus industry plays a very important socio-economic role in the national economy with an area of about 126,600 ha and a production of about 2.3 million tons (ASPAM 2018). This sector provides an important source of foreign currency per year and generates significant effects in employment through the creation about more than 35 million working days a year in orchards and at the packaging and processing industry and other activities related to citrus industry. In Morocco, citrus trees are infested by several phytophagous insects, mites, and snails, which significantly affect citrus yield quality and quantity by damaging leaves, young shoots, twigs, and fruits (Abbassi 2010; Smaili et al. 2001; Mazih 2015; Smaili 2017). Therefore, a need to develop new approaches to control these pests, using environment friendly approaches, as an alternative to chemical control is becoming a necessity for citrus producers. In the past, the control methods of the main citrus pests were applied with a few considerations of the abundance of beneficial insects and their impact on harmful pests in the Moroccan research studies (Smaili 2009; Smaili et al. 2014). However, now many reasons have greatly induced Moroccan citrus producers to enhance the IPM strategy: (i) the outbreak of new citrus pests problems such as whiteflies,

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leafhoppers, ants, and thrips (Smaili and Benyahia 2018; Smaili et al. 2018); (ii) the new requirements of importers and local market, related to ship agreed quality of citrus fruits; (iii) the exporting companies have a certified orchards with the standards and requirements of importing the fresh citrus fruit with new rigourous control requirements (e.g., China and USA requirements for citrus exporting); (iv) available effective insecticides and acaricides on control citrus pests are probably not be commercialized in the near future in Morocco (e.g., Chlorpyrifos-ethyl); (v) the need of the citrus producers for the exploration possibility for large-scale exports to new foreign markets. Indeed, new management practices such as good plant protection practices, integrated pest management strategy, classical biological control, conservative biological control, and taken into account the side effects of theses pesticides applied on citrus trees on natural enemies. In addition, worldwide, many effective species of parasitoids and predators have been found out and many species are currently available in the market. Almost 250 species of invertebrate biological control agents are used to enhance biological control and pest management worldwide (Van Lenteren et al. 2018).

Several parasitoids and predators have been reported in Moroccan citrus groves and some of them play an important role in maintaining some pests under economic threshold levels (Abbassi 1990, 2010; Smaili et al. 2010, 2013, 2014). Most of them are native species while some have been accidentally introduced or deliberately released to control certain pests. The use of natural enemies in Morocco is very old especially in citrus orchards (Smirnoff 1954, 1956; Delucchi 1963; Delucchi and Merle 1963). The first introduction of the parasitoids and/or predators to the Moroccan citrus groves (e.g., coccinellid beetles and aphelinids wasps) started almost a century ago (Smirnoff 1956; Bennassy and Euverte 1967; Euverte 1967 and EPPO 2011) already in 1921, the vedalia beetle *Rodolia cardinalis* (Mulsant, 1850) (Coleoptera: Coccinellidae) was introduced to the Moroccan citrus groves to control the cottony cushion scale *Icerya purchasi* (Maskell, 1878) (Hemiptera: Monophlebidae). The coccinellid *Cryptolaemus montrouzieri* (Mulsant, 1853) was also introduced to citrus groves during 1933 to control the citrus mealybug *Planococcus citri* (Risso, 1813) (Hemiptera: Pseudococcidae). In 1944, the coccinellid *Rhyzobius lophanthae* (Blaisdell, 1892) was introduced to control diaspines scale in citrus trees (Smirnoff 1956). During the 60s, the parasitoid *Aphytis melinus* (De Bach, 1959) and *A. lepidosaphes* (Compere, 1955) (Hymenoptera: Aphelinidae) were introduced to control mainly the dictyospermum scale *Chrysomphalus dictyospermi* (Morgan, 1889) and the California red scale *Aonidiella aurantii* (Maskell, 1878) (Hemiptera: Diaspididae) (Benassy and Euverte 1967; Euverte 1967 and EPPO 2011). A great progress, related to the use of other newly introduced beneficial insects, was made during the 70s (Benassy and Euverte 1968 a, b, and Abbassi 1974, 1975a). In the 80s and 2000s period, several others parasitoids and/or predators were intentionally introduced to control main citrus pests (Abbassi 1990, 2010; Rizqi et al. 1997a, 1997b; Abdelkhalek et al. 1998; Smaili et al. 2001; Benziane 2003 and Rizqi et al. 2003).

This article aimed to assess the species richness and potential of the parasitoids and predators in citrus orchards in Morocco.

Information sources

Available information on the parasitoids and predators associated with citrus orchards in Morocco was collected using several sources: (1) direct communication with researchers and actual users of these beneficial insects for biological control; (2) peer reviewed articles; (3) database of the European and Mediterranean Plant Protection Organization (EPPO) (www.eppo.org), the Natural History Museum (NHM) (www.nhm.ac.uk), the Centre for Agriculture and Biosciences International (CABI) (www.cabi. org), and Scholar Google (www.google.com); (4) available papers published in the national proceeding, and (5) available thesis and validated scientific reports. The species data gathered from 1920 to 2018 were summarized in a data matrix including the following variables:

Nature and target pests

Beneficial insects are indigenous (native) or exogenous (introduced) and traditionally known as parasitoids and predators. Their main hosts or preys are mostly aphids (Aphididae); scale insects (armored scale Diaspididae); soft scale from Saissetia and Coccus genera (Coccidae); Pseudococcidae (genus *Planoccocus*); Monophlebidae (cottony cushion scale *I.purchasi*); whiteflies (Aleyrodidae); mites (mainly Tetranychidae); Tortricidae (mainly *Cacoecimorpha* genus); fruit flies (Tephritidae); Gracilariidae; citrus leaf miner (mainly *Phyllocnistis citrella* Stainlon (Lepidoptera: Gracillariidae). Unknown: when there is a lack of information on targeted pests of these beneficial insects.

Type of introduction and establishment

The introduction of the parasitoids and/or predators in the Moroccan citrus orchards was considered as intentionally introduced, when the species were introduced deliberately to control targeted citrus pest and accidentally introduced, and when they were introduced by an unknown manner. The status of the introduced beneficial insects was considered as established, when the species is known to be established and observed every year; not established, when the species has not

been established and/or has not been found after their release, and unknown, when there is a lack of information on acclimatization of this beneficial insects.

Efficacy

Efficacy is considered the real impact of the parasitoids and/or predators to control one or more target pests. Five levels were proposed (adapted by Jacas et al. 2006): Effective, when the parasitoids and/or predators can reduce population of the target pest and infestation level significantly (e.g., do not exceed the economic threshold); partially effective, when the parasitoids and/or predators can control partly the population of the target pest, but with non significant reduction of infestation; low efficacy, when the beneficial species has a little impact on the population of the target pest coupled with establishment of this species once released; failure, when the parasitoids and/or predators has no effect or a very little impact on the targeted pest coupled with no real establishment (sporadic, or no establishment) of this species once released; unknown, when no information is available on the efficacy of the parasitoids and/or predators under Moroccan conditions.

Additional information and assessment

Further information on the parasitoids and/or predators in the EPPO was also provided: date reported by the EPPO; date reported in Morocco; first references to Morocco. All the above variables were estimated by a percentage (%) with the number of the parasitoids and/or predators reported out of the total number of all identified beneficial insects in citrus, called here as "Percentage of presence" (%) (Jacas et al. 2006; Roy et al. 2011). For some variables (e.g., introduced species), the percentage was also calculated by the number of the parasitoids and/or predators reported over the total number of introduced beneficial insects.

Results and discussion

Nature and type

Parasitoids and predators species are fundamental for the implementation of integrated pest management (Bonsignore and Vacante 2012; Van Lenteren et al. 2018). The parasitoids and/or predators identified in citrus counted about 105 species, 76 native species, and 29 introduced species (with 72.38 and 27.61%, respectively) (Tables 1 and 2). For the native species, predators (47.61%) are more abundant than parasitoids (24.76%). The parasitoids species belong mainly to the families: Aphelinidae, Braconidae, Encyrtidae, Eulophidae, while the predators'species belong to Coccinellidae and Phytoseiidae families. For the introduced species, their ratios are 10.47 and 17.14% for parasitoids and predators, respectively. Parasitoids and predators species belong mainly to 2 main orders: Coleoptera with 39.05% (31.43% for the natives and 7.62 % for the introduced species) and Hymenoptera with 41.90% (24.76% for the natives and 17.14% for the introduced). The other insect orders are still low and does not exceed 8.6%. The distribution of the parasitoids and/or predators grouped by the insect families is given in Fig. 1. The rate of coccinellid species was about 34.29% (26.67% for the natives and 7.62% for the introduced) and the aphelinid species about 16.19% (10.48% for the natives and 5.71% for the introduced). Species belong to families Encyrtidae, Eulophidae, Braconidae, and Phytoseiidae ranged between 7.62-9.52%, while the other families do not exceed 3%.

Target pests

Present percentage of parasitoid and predator species in Moroccan citrus groves based on target pests are given at Fig. 2. In Moroccan citrus groves, the diaspidids and aphidids are the most targeted pests for the parasitoids and/or predators. For all parasitoids and/or predators species, targeted pests were mainly Diaspididae with 30.47% (21.90 and 8.57% for the native and introduced species, respectively) and Aphididae with 17.14% (15.23 and 1.90%, respectively). This percentage did not exceed 10% for the others trophic groups. Among the introduced species, diaspidid were (34.48%), followed by the leafminer *P. citrella* (17.24%), and the white fly (17.24%) (Fig. 3). For others, trophic group percentage of presence did not exceed 7%. This is a consequence of the important richness and abundance of their main hosts, the armored scale insects and aphids, which remain the preferred target pests of many natural enemies in citrus orchards in Morocco (Abbassi 1990, 2010; Smaili et al. 2009, 2014; and Smaili 2017). In addition, arthropod pests that are exposed and not hidden and are less mobile have been more successfully controlled because their natural enemies have the capability to reach the pest (Hajek and Eilenberg 2018). Considering the introduced species only, trophic groups preferred target pests like armored scale, citrus leafminer, and white fly. This is explained in the fact that the scale insects, especially California red scale *A. aurantii*, the Chaff scale *P. pergandii*, citrus leafminer *P. citrella*, and several whiteflies species have been considered over years the most important pests in citrus orchards (Abbassi 1975b, 1975c, Abbassi 1980, Abbassi 1990, Abbassi 2010; Rizqi et al. 1997a, 1997b, 2003; Benziane 2003; Boutaleb and El Hardouni 2010and Smaili 2009, 2017).

Type of introduction

According to the types of introduction into the Moroccan citrus orchards, percentage of presence of introduced species belong to the families of Aphelinidae

Table 1 Date of first use by EPPO area, reported by EPPO for Morocco and date of first report and/or use in Moroccan citrus groves, related to native benefit species in citrus groves in Morocco

Species	Nature	Family	Date of first use by EPPO area	Reported by EPPO for Morocco	Date of first report /use in Moroccan citrus groves	First references
Ablerus (Azotus) chrysomphali (Ghesquière 1960)	Par	Aphelinidae	No	No	1950/No	(Smirnoff 1956), (Ghesquière 1960), (Bénassy and Euverte 1968a, 1968b)
Aphytis chrysomphali (Mercet, 1912)	Par	Aphelinidae	No	No	1956/No	(Thompson 1953), (Smirnoff 1956)
Aphytis hispanicus (Mercet, 1912)	Par	Aphelinidae	No	No	? /No	(Abbassi 1975c); (Rosen and DeBach 1979)
Coccophagus semicircularis (Forster, 1841)	Par	Aphelinidae	No	No	1929/No	(Smirnoff 1956)
Coccophagus lycimnia (Walker, 1839)	Par	Aphelinidae	No	No	1949/No	(Smirnoff 1956)
Coccophagus scutellaris (Dalman, 1825)	Par	Aphelinidae	No	No	1929/No	(Smirnoff 1956)
Encarsia citrina (Crawford, 1891)	Par	Aphelinidae	1984	Yes	? /No	(Thompson 1953)
Encarsia sp.	Par	Aphelinidae			/No	(Smaili et al. 2013)
Encarsia sophia (Girault and Dodd, 1915)	Par	Aphelinidae	No	No	1992/No	(Abbassi and Lakhlifi 1994)
Encarsia lounsburyi (Berlese and Paoli, 1918)	Par	Aphelinidae	No	No	1948/No	(Smirnoff 1956)
Marietta leopardina (Motschulsky, 1863)	Par	Aphelinidae		No	/No	(Ghesquiere 1960), (Benassy and Euverte 1967) , (Hayat 1986)
Aphidius ervi (Haliday, 1834)	Par	Braconidae	1995	Yes	? /No	(Stary and Sekkat 1987)
*Aphidius sp.*probably *Aphidius colemani* (Viereck)	Par	Braconidae	No	No	? /No	(Smaili et al. 2009, 2013)
Lysiphlebus fabarum (Marshall, 1896)	Par	Braconidae	No	No	? /No	(Stary and Sekkat 1987)
Microgaster sp1. (Latreille, 1804)	Par	Braconidae			/No	(Delucchi and Merle 1962)
Microgaster sp.2 (Latreille, 1804)	Par	Braconidae			/No	(Delucchi and Merle 1962)
Psyttalia concolor (Szepligeti, 1910)	Par	Braconidae	1914	No	? /No	(Malausa et al. 2008)
Anagyrus pseudococci (Girault, 1915)	Par	Encyrtidae	1995	Yes	? /No	(Smaili et al. 2013), Rizqi and Bihi Com. pers.
Coccidoxenoides perminutus (Girault, 1915)	Par	Encyrtidae	No	No	? /No	(Smaili et al. 2013) Rizqi and Bihi Com. Pers.
Habrolepis diaspidi (Risbec, 1951)	Par	Encyrtidae	No	No	1965/No	(Compere and Annecke 1961), (Delucchi and Traboulsi 1965), (Benassy and Euverte 1967)
Habrolepis dalmanni (Westwood, 1837)	Par	Encyrtidae	No	No	1950/No	(Thompson 1953), (Smirnoff 1956)
Leptomastidea abnormis (Girault, 1915)	Par	Encyrtidae	1984	Yes	? /No	(OILB 1971), (Noyes and Hayat 1994), Abdelkhalek et al. (1998)
Elachertus affinis (Masi, 1911) (syn. *Artaeus* Walker)	Par	Eulophidae	?		/No	(Delucchi and Merle 1962)
Cirrospilus pictus (Nees, 1834)	Par	Eulophidae	No	No	/No	FAO (1996), (Smaili et al. 1999b)
Cirrospilus vittatus (Walker, 1838)	Par	Eulophidae	No	No	/No	(FAO 1996)
Pnigalio sp.	Par	Eulophidae	No	No	/No	(FAO 1996)
Euseius scutalis (Athias-Henriot, 1958)	Pred	Phytoseiidae	No	No	? /No	(Meyerdirk and Coudriet 1986), (McMurtry and Bounfour 1989)

Table 1 Date of first use by EPPO area, reported by EPPO for Morocco and date of first report and/or use in Moroccan citrus groves, related to native benefit species in citrus groves in Morocco *(Continued)*

Species	Nature	Family	Date of first use by EPPO area	Reported by EPPO for Morocco	Date of first report /use in Moroccan citrus groves	First references
Euseius stipulatus (Athias-Henriot, 1960)	Pred	Phytoseiidae	No	No	? /No	(Bounfour and McMurtry 1987)
Iphiseius degenerans (Berlese, 1889)	Pred	Phytoseiidae	1993	No	1981/No	(McMurtry and Bounfour 1989)
Phytoseiulus persimilis (Athias-Henriot, 1957)	Pred	Phytoseiidae	1968	no	? /No	(McMurtry and Bounfour 1989)
Typhlodromus phialatus (Athias-Henriot, 1960)	Pred	Phytoseiidae	No	No	1989 /No	(McMurtry and Bounfour 1989)
Amblyseius andersoni (Chant, 1957)	Pred	Phytoseiidae	No	No	2003 /No	(Tixier 2013)
Typhlodromus foenilis (Oudemans, 1930)	Pred	Phytoseiidae	No	No	2013 /No	(Tixier 2013, Tixier et al. 2016)
Harpalus sp.	Pred	Carabidae	No	No	2009/No	(Smaili 2009), (Smaili et al. 2013)
Pseudoophonus rufipes (De Geer, 1774)	Pred	Carabidae	No	No	2009/No	(Smaili 2009), (Smaili et al. 2013)
Cicindella sp.	Pred	Cicindellidae	No	No	2009/No	(Smaili et al. 2009)
Adalia decempunctata (L., 1758)	Pred	Coccinellidae	No	No	1931/No	(Smirnoff 1956), (Smaili et al. 2010-Smaili et al. 2013)
Adalia bipunctata (L., 1758)	Pred	Coccinellidae	Yes	Yes	? /No	(Smaili et al. 2006, Smaili et al. 2010a, Smaili et al. 2013)
Chilocorus bipustulatus (L., 1758)	Pred	Coccinellidae	1959	Oui	1954/Yes*	Smirnoff (1954, 1956)
Clitosthetus arcuatus (Rossi, 1794)	Pred	Coccinellidae	No	No	1931/No	(Smirnoff 1956), (Abbassi 1990)
Coccinella septempunctata (L., 1758)	Pred	Coccinellidae	1980	Yes	1929/No	(Smirnoff 1956), (Smaili et al. 2010, 2013)
Exochomus nigromaculatus (Goeze, 1777)	Pred	Coccinellidae	No	No	1933/No	(Smirnoff 1956), (Smaili et al. 2010, 2013)
Exochomus quadripustulatus (L., 1758)	Pred	Coccinellidae	No	No	1949/No	(Smirnoff 1956), (Smaili et al. 2013)
Harmonia quadripunctata (Pontoppidan, 1763)	Pred	Coccinellidae	No	No	1956/No	(Smirnoff 1956), (Smaili et al. 2013)
Hippodamia variegata (Goeze, 1777)	Pred	Coccinellidae	no	no	1931/No	(Smirnoff 1956) (Smaili et al. 2013)
Hyperaspis reppensis (Herbst, 1783)	Pred	Coccinellidae	No	No	1953/No	(Smirnoff 1956), (Abbassi 1990)
Nephus ulbrichi (Fursch, 1977)	Pred	Coccinellidae	No	No	1949/No	(Smaili et al. 2013)
Oenopia conglobata (L., 1758)	Pred	Coccinellidae	No	No	2010 (1956 in Morocco) /No	(Smirnoff 1956), (Smaili et al. 2013)
Oenopia doublieri (Mulsant, 1846)	Pred	Coccinellidae	No	No	1953/No	(Smirnoff 1956)
Platynaspis luteorubra (Goeze, 1777)	Pred	Coccinellidae	No	No	1933/No	(Smirnoff 1956) (Smaili et al. 2013)
Pharoscymnus setulosus (Chevrolat, 1861)	Pred	Coccinellidae	No	No	2011 (1952 in Morocco) /No	(Smirnoff 1956), (Smaili et al. 2013)
Propylea quatuordecimpunctata (L., 1758)	Pred	Coccinellidae	No	No	2007/No	(Smaili et al. 2006, 2010, 2013)
Rhyzobius chrysomeloides (Herbst, 1792)	Pred	Coccinellidae	No	No	Before 1990/No	(Abbassi 1990)

Table 1 Date of first use by EPPO area, reported by EPPO for Morocco and date of first report and/or use in Moroccan citrus groves, related to native benefit species in citrus groves in Morocco *(Continued)*

Species	Nature	Family	Date of first use by EPPO area	Reported by EPPO for Morocco	Date of first report /use in Moroccan citrus groves	First references
Rhyzobius litura (Fabricius, 1787)	Pred	Coccinellidae	No	No	1956/No	(Smirnoff 1956)
Scymnus apetzi (Mulsant, 1846)	Pred	Coccinellidae	No	No	1930/No	(Smirnoff 1956), (Smaili et al. 2010, 2013)
Scymniscus biguttatus (Mulsant, 1850)	Pred	Coccinellidae	No	No	1956/No	(Smirnoff 1956), (Smaili et al. 2013)
Scymnus levaillanti (Mulsant, 1850)	Pred	Coccinellidae	No	No	1951/No	(Smirnoff 1956)
Scymnus interruptus (Goeze, 1777)	Pred	Coccinellidae	No	No	1931/No	(Smirnoff 1956)
Scymnus marinus (Mulsant, 1850)	Pred	Coccinellidae	No	No	1951/No	(Smirnoff 1956)
Stethorus punctillum (Weise, 1891)	Pred	Coccinellidae	1995	Yes	? /No	(Smaili et al. 1999a, 2010)
Scymnus sp.1	Pred	Coccinellidae	No	No	2007/No	(Smaili et al. 2010, 2013)
Scymnus sp.2*; probably Scymnus rufipes* (Fabricius, 1798)	Pred	Coccinellidae	No	No	2008/No	(Smaili et al. 2010, 2013)
Scymnus subvillosus (Goeze, 1777)	Pred	Coccinellidae	No	No	1931/No	(Smirnoff 1956), (Smaili et al. 2009, 2010)
Scymnus suturalis (Thunberg, 1795)	Pred	Coccinellidae	No	No	1927/No	(Smirnoff 1956)
Cybocephalus sp.	Pred	Nitidulidae	No	No	1956 /No	(Smirnoff 1956)
Cybocephalus rabaticus (Smirnoff 1956)	Pred	Nitidulidae	No	No	1952/No	(Smirnoff 1991), (Arahou 2008)
Aphidoletes Aphidimyza (Rondani, 1847)	Pred	Cecidomyiidae	1985	Yes	? /No	?
Leucopis griseola (Fallén, 1823)	Pred	Chamaemyiidae	No	No	1956 /No	(Smirnoff 1956)
Simosyrphus sp.	Pred	Syrphidae	No	No	1956 /No	(Smirnoff 1956)
Anthocoris sp.	Pred	Anthocoridae	No	No	1956 /No	(Smaili 2009)
Orius sp.	Pred	Anthocoridae	No	No	? /No	(Smaili 2009)
Cardiastethus nazarenus (Reuter, 1884)	Pred	Anthocoridae	No	No	1956 /No	(Smirnoff 1956)
Chrysoperla carnea (Stephens, 1836)	Pred	Chrysopidae	1987	Yes	? /No	?
Conwentzia psociformis (Curtis, 1834)	Pred	Coniopterigidae	No	No	? /No	(Smaili 2009, 2013)
Aeolothrips sp.	Pred	Aeolothripidae	No	No	? /No	?
Franklinothrips sp.	Pred	Aeolothripidae	No	No	? /No	Personal observation

Para parasitoid; *Pred.* predator
*Biological control only with *C.bipustulatus var .iranensis*

Table 2 Date of first use by EPPO area, reported by EPPO for Morocco, and date of first report and/or use in Moroccan citrus groves, related to introduced benefit species in citrus groves in Morocco

Species	Origin	Nature	Family	Date of first use by EPPO area	Release reported by EPPO for Morocco	Date of first report/use in Moroccan citrus groves	First references
Aphytis lepidosaphes (Compere, 1955)	China	Par	Aphelinidae	1956	No	?/No	EPPO
Aphytis lingnanensis (Compere, 1955)	Est Asie-Chine (via Calfornie)	Par	Aphelinidae	1960	Yes	1965/No	(Euverte 1967), (Benassy and Euverte 1967a, Bénassy and Euverte 1968a)
Aphytis melinus (DeBach, 1959)	India-Pakistan	Par	Aphelinidae	1962 (probably 1961)	Yes	1961/Yes	(Euverte 1967), (Bénassy and Euverte 1967a, Bénassy and Euverte 1968a)
Cales noacki (Howard, 1907)	Chile	Par	Aphelinidae	1970	Yes	1970/Yes	(Abbassi 1974, 1975b)
Encarsia lahorensis (Howard, 1911)	India/Pakistan	Par	Aphelinidae	1973	No	1973/Yes	(Orlinski and Bassova 1996)
Eretmocerus debachi (Rose and Rosen, 1992)	Japan- North America	Par	Aphelinidae	1982	No	1992/Yes	(Abbassi and Lakhlifi 1994)
Lysiphlebus testaceipes (Cresson, 1880)	Cuba	Par	Braconidae	1990	Yes	2002/No	(EPPO 2002)
Ageniaspis citricola (Logvinovskaya, 1983)	Thailand (Florida)	Par	Encyrtidae	1994	Yes	1995/Yes	(FAO 1996) (Abbassi et al. 1997), (Rizqi et al. 1997b)
Comperiella bifasciata (Howard, 1906)	South China (via Califournie)	Par	Encyrtidae	1924	Yes	?/No	(Abbassi 1990), (Noyes and Hayat 1994)
Leptomastix dactylopii (Howard, 1885)	Neotropique Brasil	Par	Encyrtidae	1992	Yes	1997?/No	(Noyes and Hayat 1994), (Abdelkhalek et al. 1998)
Metaphycus flavus (Howard, 1881)	-	Par	Encyrtidae	1999	No	2004/ ?	(OILB 1971),
Metaphycus helvolus (Compere, 1926)	South Africa	Par	Encyrtidae	1992		?	(Noyes and Hayat 1994)
Cirrospilus ingenuus (Gahan, 1932)	South East Asia (via Australie)	Par	Eulophidae	No	No	1996/Yes	(FAO 1996), (Rizqi et al. 2003)
Citrostichus phyllocnistoides (Narayan, 1960)	South China (via Espagne)	Par	Eulophidae	No	No	1999/Yes	(Smaili et al. 2001b); (Rizqi et al. 2003)
Quadrastichus citrella (Reina and LaSalle 2004)	South Asia (viaEspagne	Par	Eulophidae	No	No	1997/Yes	(Smaili et al. 2001b); (Rizqi et al. 2003), (Reina and LaSalle 2004)
Semielacher petiolatus (Girault, 1915)	Australia	Par	Eulophidae	No	No	1996/Yes	(FAO 1996), (Rizqi et al. 1997a)
Amitus spiniferus (Brethes, 1914)	Peru	Par	*Platygasteridae*	1971	No	1975/Yes	Abbassi, Com. per. (Smaili et al. 2013);
Diachasmimorpha	Spain	Par	Braconidae	No	No	2016/No	(Mazih et al. 2016)

Table 2 Date of first use by EPPO area, reported by EPPO for Morocco, and date of first report and/or use in Moroccan citrus groves, related to introduced benefit species in citrus groves in Morocco *(Continued)*

Species	Origin	Nature	Family	Date of first use by EPPO area	Release reported by EPPO for Morocco	Date of first report/use in Moroccan citrus groves	First references
longicaudata (Ashmead)							
Neoseiulus californicus (McGregor, 1954)	S No Amérique /California -Méditerranée	Pred	Phytoseiidae	1985	No	2009(< 2007 in Morocco /Yes	(Kreiter et al. 2007), (Smaili et al. 2013)
Amblyseius swirskii (Athias-Henriot, 1962)	-	Pred	Phytoseiidae			2014 (< 2014 in Morocco) /Yes	(Smaili 2017)
Cryptolaemus montrouzieri (Mulsant, 1853)	Australie	Pred	Coccinellidae	1908	Yes	1933/Yes	(Smirnoff 1956)
Delphastus catalinae (Horn, 1895)	Nearctic/ Neotropique (America)	Pred	Coccinellidae	1993	No	2011/No	(Smaili et al. 2013)
Exochomus nigropictus (Fairmaire, 1876)	-	Pred	Coccinellidae	No	No	2010/No	(Smaili et al. 2010a, Smaili et al. 2013)
Hyperaspis algirica (Crotch, 1874)	-	Pred	Coccinellidae	No	No	2002/No	(Smaili et al. 2010a, Smaili et al. 2013)
Hyperaspis pumila (Mulsant, 1987)	-	Pred	Coccinellidae	No	No	2002/No	(Smaili et al. 2006, Smaili et al. 2010a, Smaili et al. 2013)
Nephus peyerimhoffi (Sicard, 1923)	-	Pred	Coccinellidae	No	No	2011/No	(Smaili et al. 2013)
Rodolia cardinalis (Mulsant, 1850)	Australia	Pred	Coccinellidae	1897	yes	1921/Yes	(Smirnoff 1956) (Smaili et al., 2010a, 2013)
Rhyzobius lophanthae (Blaisdell, 1892)	Australia	Pred	Coccinellidae	1980	yes	1944/Yes	(Smirnoff 1956)
Episyrphus balteatus (DeGeer, 1776)	Europe	Pred	Syrphidae	1995	yes	-/No	(Dirickx 1994), (Smaili et al. 2009)

Para parasitoid; *Pred.* predator

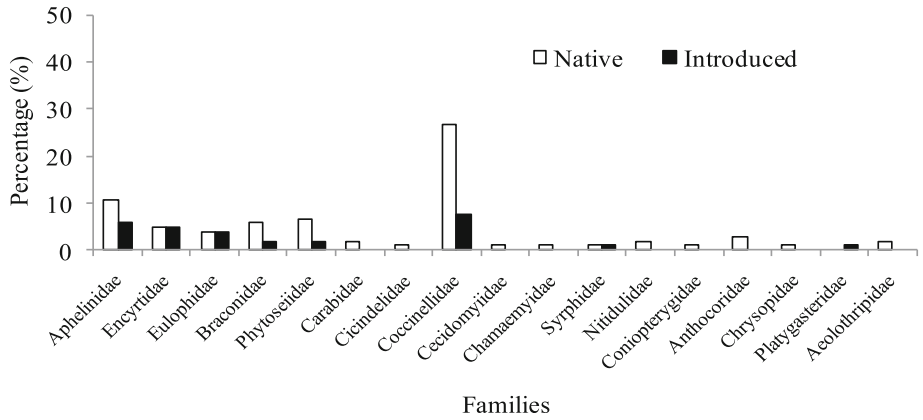

Fig. 1 Percentage of presence (%) of beneficial species grouped by families in Moroccan citrus orchards (*N* = 105)

(20.68%), Encyrtidae (17.24%), Eulophidae (13.79%), Braconidae (6.89%), Coccinellidae (27.58%), Phytoseiidae (6.89%), Syrphidae (3.44%), and Platygasteridae (3.44%). The introduced species have been used deliberately to control main target pests in classical biological control reached (68.96%), mainly for Aphelinidae, Encyrtidae, Eulophidae, Coccinellidae, and Phytoseiidae. The other introduced species have been found accidentally at the citrus trees representing 31.03%. The major voluntarily introduced beneficial species to Morocco came from different origins, especially Spain, South East Asia (via INRA Antibes, France and Florida or California), and Australia. For those introduced accidentally, ladybeetle species are the most noted. In Europe, the majority of beneficial species have been introduced by accident, while a third of the species were intentionally introduced for biological control (Roy et al. 2011). In Morocco, during the period of 1921 to 1944, 3 voluntary introductions of coccinellids were made (Smirnoff 1956; EPPO 2011). Indeed, already in the year 1921, *R. cardinalis* remained the first and the main beneficial insect introduced to the Moroccan citrus orchards to control *I. purchasi*. Twelve years later, the ladybeetle *C. montrouzieri* was also introduced for biological control of the meal bugs. Then in 1944, there was a third new introduction of *R. lophanthae* to combat the armored scale on citrus, particularly *A. aurantii* (Smirnoff 1956). During the period of 1961 and 1970, 4 major voluntary introductions were made (Bénassy and Euverte 1968a; Bénassy and Euverte 1968b; Abbassi 1974; Abbassi and Euverte 1974). Three species to control armored scale, *A. aurantii* and another species Aphelinid species *C. noacki*, to reduce the whitefly *A. flocossus*. These species were very abundant and important during this period. Since then until the 90s, very few new introductions were made. This is in case of the parasitoid, *A. spiniferus,* introduced to control *A. floccosus* in 1975 (Abbassi 2010). This could be explained by the growing trade, the emergence, the availability, and the efficiency of synthetic chemicals. This is also true for the adoption at this time of the classical chemical control, as an effective control solution. It is important to consider that the new major introductions of parasitoids and/or predator species have been made since the nineties, especially for the purpose of a classical biological control. This is the case of introduced species against citrus leafminer *P. citrella*, as a new pest

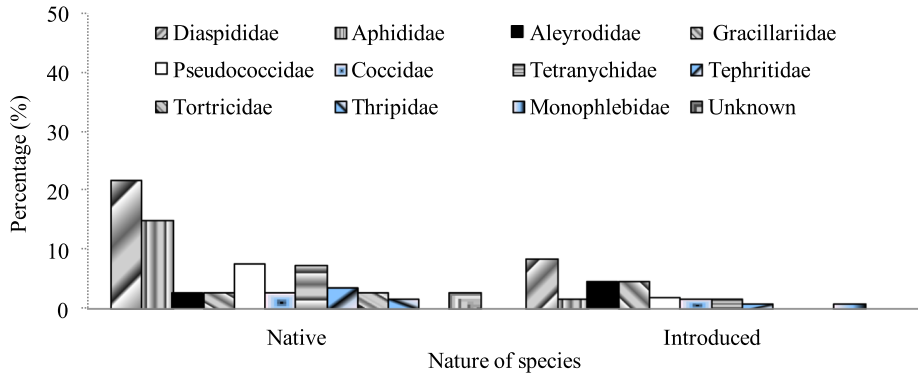

Fig. 2 Percentage of presence (%) of all beneficial species according to their targeted pests in Moroccan citrus orchards (*N* = 105)

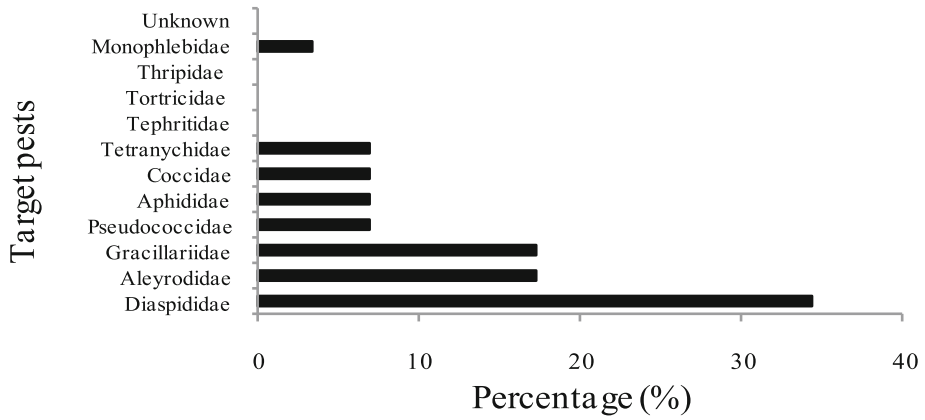

Fig. 3 Percentage of presence (%) of introduced species according to their targeted pests in Moroccan citrus orchard (*N* = 29)

emerging in 1994 in Morocco (Belarbi and Abir 1995). Theses introductions were later coincided with the implementation of integrated pest management program and also the organic agriculture protection in several agricultural sectors in Morocco.

The introduction of the certification procedure and the elimination of several active ingredients from commercial markets in Morocco encouraged more citrus producers to improve their integrated pest management strategy and use the natural enemies in their pest control management. Except the new introduction in citrus orchards, like the predators *Neoseiulus californicus* (Mc Gregor) (Acari: Phytoseiidae) and *Amblyseius swirskii* (Athias-Henriot) (Acari: Phytoseiidae) against the oriental mite *E. orientalis*, no new deliberate introduction after the 2000s has been done to our knowledge (Smaili et al. 2013; Smaili 2017). However, more *A.melinus* and many other parasitoids and predators were released in citrus groves in the context of the IPM. This is the case for *S. puntillum* to control spider citrus mite (Nia et al. 2008), *R. cadinalis* to control *I. purchasi* (Nafide et al. 2010), and *C. decempunctata* to control aphids (Smaili et al. 2014). The introduced parasitoid *A. melinus* remains the beneficial insect released widely in classical biological control in the main Moroccan citrus area (Abbassi 1990, 2010). Other species were newly introduced in the year 2011 but in an accidental way. This is the case of the ladybeetle *D. catalinae* (Smaili et al. 2013), which is recognized as a potential predators and very effective against whiteflies (Simmons and Legaspi 2004). The efficacy of this predator is currently considered as unknown in Morocco, because the low infestation of citrus whiteflies located alongside the coastal regions in the northwest part of Morocco, except some citrus groves located at Larache, Tazi, and Belkseri area with high infestations of *A. floccosus* during the 3 last years.

Except new introduction of *Diachasmimorpha longicaudata* (Ashmead) (Hymenoptera: Braconidae) against the Mediterranean fruit fly *Ceratitis capitata* (Diptera: Tephritidae), an important pest for Moroccan citrus growers (Smaili et al. 1999a, 2016; Mazih 2015; Mazih et al. 2016; Smaili 2017). It is also true in terms of citrus thrips whitch has a new economic importance on some citrus groves located in the south part of Morocco (Smaili et al. 2018).

The newly introduced species are significant in terms of their positive impact on the economy or the environment, particularly those introduced for biological control objective (Roy et al. 2011; Van Lenteren et al. 2018). The authors reported that a number of recent successes showed how biological control can save agricultural production when pesticides fail or are not available. According to the authors, in some cases, the new introduction may also have a negative impact, because of the interference of this exogenous species with the indigenous. In Morocco, among the all introduced species, no species has been reported to be harmful to this date. In many countries, the introduction of ladybird *Harmonia axyridis* Pallas (Coleoptera: Coccinellidae), originated from China, known as aphidophagous species that was imported for a biological control against aphids, but recently it has become a harmful insect for native aphidophagous species (Osawa 2011).

Establishment

Among the introduced species, a high proportion of parasitoids and predator species was established. A part of 79.31% of all introduced species has been well established after their introduction (and/or released) in citrus groves under the Moroccan conditions. Percentage of establishment of the introduced species grouped in the families are given in Fig. 4. The Encyrtidae, Eulophidae, and Platygasteridae families included few species that have not been established after their releases (less than 4%). The Eulophidae, Coccinellidae, and Braconidae remained the only families that include introduced species with unknown level of establishment (3.44%).

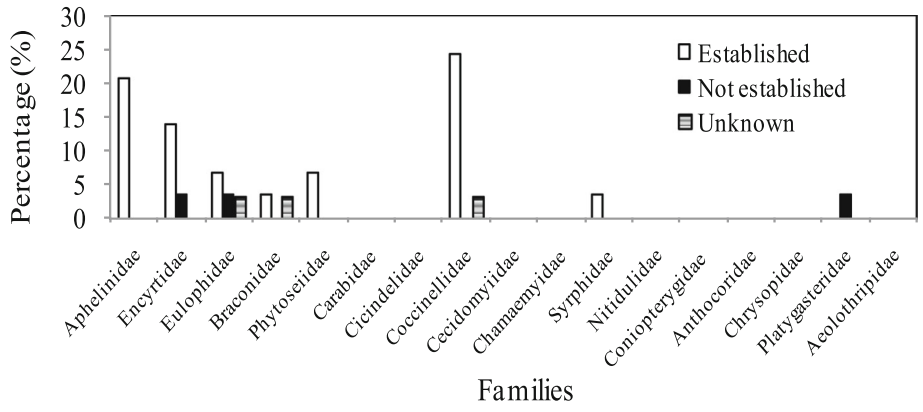

Fig. 4 Percentage of presence (%) of introduced species grouped by families according to their establishment in Moroccan citrus orchard (*N* = 29)

Probably, ecological factors can limit their establishment, a new agro-ecosystem after their introduction. This is the case of *A. citricola* that did not perform well and failed to reduce leafminer population, after many release in several area of Morocco (Smaili et al. 2001b and Rizqi et al. 2003). Cold winter, and not arid or hot summer, seems to be the main reasons of the failure of this encyrtid in Mediterranean areas (Garcia-Mari et al. 2004). The same authors reported that in Spain, *A. citricola* was recovered in summer in many release points, reaching nearly 50% of parasitism and dispersing more than 300 m, but it was not able to overwinter.

Efficacy

Presence percentage of parasitoids and/or predators species according to their efficacy in controlling main citrus pests is presented in Fig. 5. Among all identified parasitoids and predators species, only few species are effective or partially effective. Among all parasitoids and predators species, 3.80% is represented as effective species (0 and 3.80% for the native and introduced species, respectively). The percentage of presence of the partially effective species is about 15.23% (5.71 and 9.52%, respectively). The species that have low efficacy or failed in controlling their target pests represent 50.47 and 27.61%, respectively. It is important to note that 21.90% (native species), and only 5.71% (introduced species) are represented by the species which failed to control their targeted pests. Species which efficacy is unknown represent only 2.85%.

For native species, the majority of species is not effective and does not control their target pest. Among the only native species (*N* = 76), the species characterized with low efficacy or failed to control their targeted pests, represent a higher percentage (61.84 and 30.26%, respectively). Conventionally, the native natural enemies are always known by very limited effectiveness against the main pests. Advances will hinge on improved holistic understanding of the ecological roles of this species, particularly coccinellids and their ability to complement other beneficial species (Michaud 2012). This is because conservation biological control should focus on

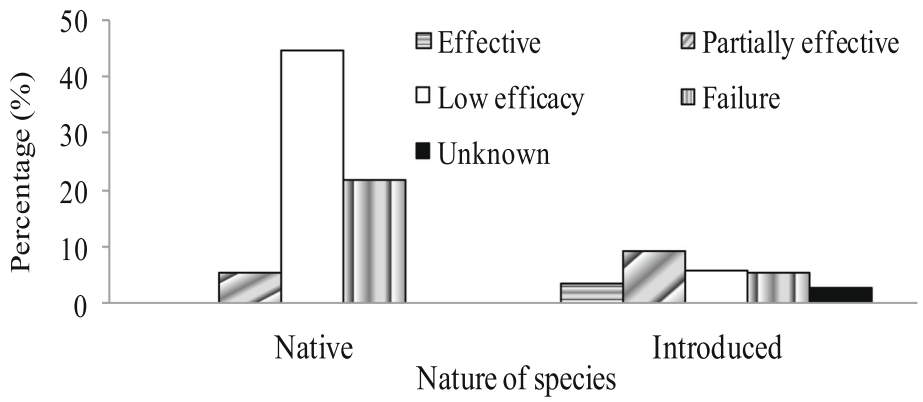

Fig. 5 Percentage of presence (%) of all beneficial according to their efficacy in Moroccan citrus orchard (*N* = 105)

enhancing benefic species arthropod habitats by increasing the natural resources required for survival and reproduction (Botha et al., 2017). The same authors reported that this requires knowledge about the specific requirements of these benefic species, which can only be acquired from species-level data.

Considering all introduced species, few species were represented as effective (< 14%) or partially effective (the third). Among the all introduced species (for intentionally introduced and unknown), 13.79 and 34.48% were considered as effective and partially effective, respectively (Fig. 6). Aphelinidae, Encyrtidae, Eulophidae, Coccinellidae, and Phytoseiidae families, include effective species and partially effective. The families like Encyrtidae (3.44%), Eulophidae (3.44 %), Platygasteridae (3.44%), and Coccinellidae (10.34%) present some introduced species that failed to control their targeted pests. This is the case of the *S. petiolatus* and *C. phyllocnistoides*, major parasitoids Eulophidae of *P. citrella* (Abbassi et al., 1999; Smaili et al. 1999b, 2001; Rizqi et al. 2003 and Abbassi 2010). Species that have failed to control target pests are important. This is the case of *A. citricola* and *Q. citrella*, 2 introduced parasitoids species of *P. citrella* (Abbassi et al. 1997; Smaili et al. 2001; Rizqi et al. 2003; Reina and LaSalle 2004). Encyrtidae, Braconidae, and Coccinellidae presented some introduced species that are to control their target pests are considered as unkown (< 4%).

Considering introduced species used in the term of classical biological control only, 20 and 40% of the species are considered as very effective or partially effective, respectively; versus the species with low efficacy (15%) or failed to control their target pests (15%) (Fig. 7). It is important to note that when the beneficial species are specific, the effectiveness in controlling targeted pests is always very high. In Moroccan conditions, this is true (after repeated release) in the case of parasitoid *A. melinus* against *A. aurantii* (El Kaoutari et al. 2004; Jebbor et al. 2008; Smaili 2009; Abbassi 2010); for *R. cardinalis* against *I. purchasi* (Nafid et al., 2010) and for the parasitoids *S. petiolatus* and *C. phyllocnistoides* against *P. citrella* (Rizqi et al. 2003). The importance of this specificity becomes more apparent at every new introduction of the citrus whitefly. This is the case of *C. noacki* against *A. floccosus*; *E. debachi* against *P. myricae* and finally *E. lohrensis* against *D. citri* (Abbassi 2010). This specificity has been reported in several countries (Orlinski and Bassova 1996; Argov et al. 1999; Fadamiro et al. 2008). The good plant protection practices consist of the use of specific beneficial insects to control a target pest, based mainly on the phylogenetic knowledge of the parasitoid and its host (Malausa et al. 2008).

Parasitoids and/or predators in Morocco in relation with EPPO database

Further information on parasitoids and/or predators species in relation to the EPPO database, like date reported; date reported in Morocco; and first references to Morocco are shown in Tables 1 and 2. Some of these introduced parasitoids and/or predators and their uses in biological control were not mentioned by many international scientist web-database. This is the case of *E. nigropictus* identified during 2010 or *N. peyerimhoffi* and *D. catalinae* mentioned in 2011 (Smaili et al. 2013). It is the same for database of EPPO, particularly for old introductions of natural enemies (e.g., *A. spiniferus* and *Q. citrella*) and new introduction (e.g., *N. californicus* and *A. swirskii*) (Smaili 2017). This could probably be explained by the scarcity of their population and their low impact on the target pests (low importance), and maybe also the absence of international publications mentioning their impact on main citrus pests in Morocco.

Conclusion

Among the beneficial insects (parasitoids and/or predators) identified in citrus groves of Morocco, only a small fraction of the introduced species found, attack armored scale and aphids. Considering only introduced species used in classical biological control context, many species

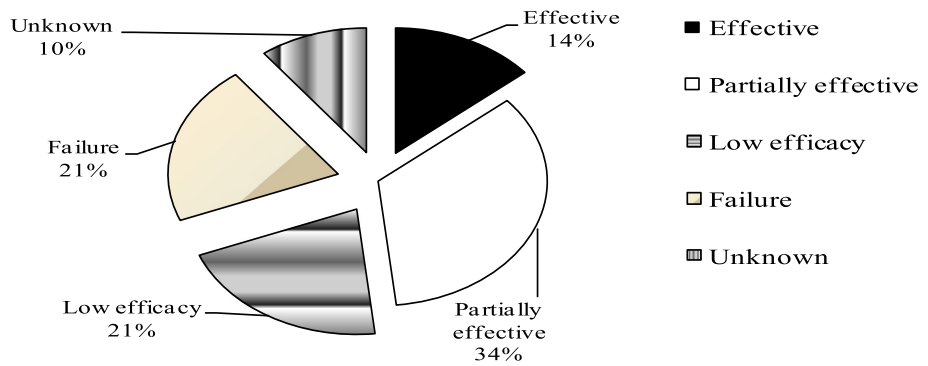

Fig. 6 Percentage of presence (%) of introduced species according to their efficacy in Moroccan citrus orchard (*N* = 29)

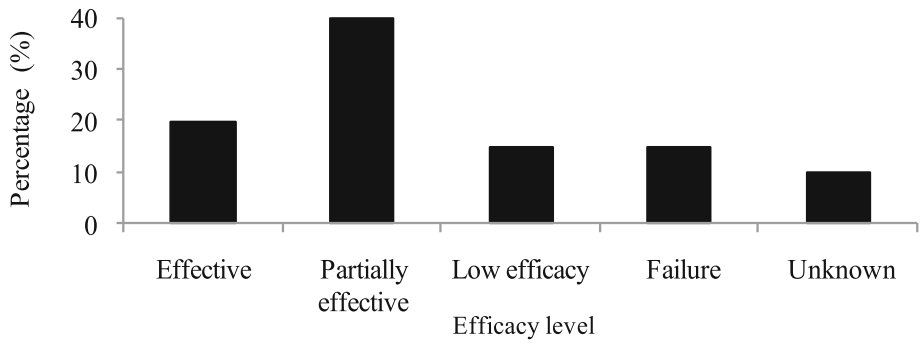

Fig. 7 Efficacy level of introduced species used in term of classical biological control only in Moroccan citrus orchard ($N = 20$)

are considered effective or partially effective. This review article may facilitate future investigations on parasitoids and predators species to increase their potential in citrus orchards and to enhance the role of biological control agent (e.g., augmentative biological control) and the integrated pest management services, particularly for citrus in the Mediterranean regions.

Abbreviations

Ha: Hectare; ASPAM: Moroccan Association of Citrus producers; IPM: Integrated pest managmement; USA: United States of America; INRA: National Agricultural Research Institute; e.g.: Example; N: Total number; Para:: Parasitoid; Pred.: Predator

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Authors' contributions

SMC: Conceptualization, data curation, monitoring-compilation-investigation, methodology, interpretation of data; writing-original draft, writing-review-editing, supervision, and critical revision of the manuscript for important intellectual content. BJA: Methodology, interpretation of data; investigation, writing-review-editing, and critical revision of the manuscript for important intellectual content. BA: Methodology, interpretation of data, supervision; interpretation of data; investigation, writing-review-editing, and critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript.

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Availability of data and materials

The data and material of this manuscript are available on reasonable request.

Ethics approval and consent to participate

We agree to all concerned regulations. This article does not contain any studies with human participants or animals or human tissue.

Consent for publication

We agree to publish this scientific paper at the EJBPC. The manuscript has not been published in completely or in part elsewhere.

Competing interests

The authors declare that they have no competing interests.

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