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Mycophagy in Coccinellidae: A review

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Introduction

Coccinellids commonly known as lady bird beetles are the most familiar insects to everyone from their childhood. It is well known that these fascinating insects are voracious predators of sternorynchous hemipterans. They even have a history of the first successful classical biological control involving the introduction of the vedalia beetle, *Rodolia cardinalis* (Mulsant), to control cottony cushion scale, *Icerya purchasi* Maskell), on citrus plants in California during the late 1880s (Caltagirone and Doutt, 1989). Despite the stereotype of the family Coccinellidae as zoophagous few of them are phytophagous (Epilachnini and genus *Bulaea*), a lesser-known fact that certain coccinellids are mycophagous feeding on various fungi either as facultative or obligate feeders. The term mycophagy refers to a wide range of nutritional modes adopted by insects in which fungi are selectively favored as a food source (Murrin, 1996).

Origin of mycophagy in coccinellids

The evolution of Coccinellidae includes feeding transitions that span kingdoms of life (plant, animal, and fungus) and trophic levels (e.g., herbivore and primary carnivore). Phytophagy within the Epilachninae and mycophagy (both facultative and obligative) within the Coccinellinae have evolved from a common coccidophagous ancestor (Giorgi *et al*., 2009) that, in turn, may have been derived from an ancient mycophagous group, the Cerylonid series, from which all coccinellids are descended (Sasaji, 1968; Leschen, 2000; Giorgi *et al*., 2009; Sutherland and Parrella, 2009). Several others believe that the mycophagy may have been associated with the early evolution of aphidophagy (Lawrence and Hlavac, 1979; Crowson, 1981; Thomas, 1993). The ancestral ladybird beetles first consumed the sooty molds of ascomycotina developed on the honey dew excreted by hemipteran insects and later evolved as the predators of hemipteran insects (Leschen, 2000).

Coccinellids feeding on fungi

Facultative feeders

Mycophagy is known to occur in many clades of Coccinellidae. Facultative feeders largely are observed in the aphidophagous coccinellids of tribe Coccinellini where they feed on fungi as non-prey foods in their diet. Many researchers reported the presence of fungal spores in the gut analysis of coccinellids. The first establishment of consumption of fungi by coccinellids was by Forbes (1881, 1883) who examined the gut contents of agricultural coccinellids. Together with the pollen, the gut contents comprised approximately half of the estimated volume of fungal material in all the eight species of coccinellids examined. About 90% of food observed in the guts of *Coccinella novemnotata* was *Ustilago* and *Helminthosporium* spores. Triltsch (1997) reported the frequent occurance of the *Alternaria* (80%) and *Puccinia* (20%) fungal spores in the gut contents of *Coccinella septumpunctata* adults. Molecular analysis revealed the presence of powdery mildew fungal spores in the guts of *C. septumpunctata* when fed either on powdery mildew or on a mixed diet of aphid and powdery mildew revealing the utilization of fungus in their diet (Radonjic *et al*., 2018).

The polyphagous coccinellids of tribe Tytthaspidini with two genera, *Tytthaspis* Crotch and *Bulaea* Mulsant often feed on fungi and compliment their diet with pollen and some plants. Turian (1969) gave the first detailed information on food of *Tytthaspis sedecimpunctata* revealing that it feeds on Erysiphaceae and proposed the term "micromycetophagy" to describe the feeding behavior on lower fungi (micromycetes). Ricci (1982) discovered the fungal spores of *Alternaria* and *Cladosporium* Link ex Fries, along with pollen, Acari, and Thysanoptera remnants, in the gut contents of *Tytthaspis sedecimpunctata* (L.).

Obligate feeders

The obligate mycophagous species of the genera *Psyllobora*, *Vibidia*, *Illeis* and *Halyzia* belong to the tribe Halyziini feed on lower fungi, especially those belonging to Erysiphales (Vandenberg, 2002; Ślipiński & Tomaszewska, 2010). Both the grubs and adults are known to reduce the spore load on the leaves of crop plants by feeding on the fungal patches (Fig. 1). Turian (1969) also observed *Psyllobora vigintiduopunctata* larvae and adults feeding on various Erysiphaceae. However, Culik *et al*. (2011) published the first report of *Psyllobora rufosignata* feeding on the rust fungus *Phakopsora euvitis* which was also the first record of any Halyziini species feeding on any species of Basidiomycota.

Morphological adaptations

The morphology of the mandibles in coccinellidae varies with the feeding habit (Kovar, 1996; Samways *et al*., 1997). Most mycophagous species exhibit morphological feeding adaptations that facilitate the collection, scraping and consumption of spores from fungal material, similar to those rakes and combs used in pollinivory (Lawrence, 1989). Specifically, the members of the Halyziini possess a series of secondary teeth on the ventral apical tooth which varies with the species. The prostheca of the mandibles extends ventrally from the base of the mandibles and fringed with setae which are well developed in *Tytthaspsis sedecimpunctata* (Ricci, 1982; Kovar, 1996; Samways *et al*., 1997). Other facultative feeders lack these morphological adaptations to fungal feeding, yet this does not negate the importance of fungus in their life histories.

Fungus as olfactory cues

Mycophagous ladybirds are attracted to the "moldy" odorants which are the fungal volatiles emitted by the powdery mildew infected plants and these cues can play important roles in ladybird foraging behavior. *P. vigintimaculata* beetles showed strong preference to characteristic odors released by squash plants infected by powdery mildew especially to 1-octen-3-ol, which was the most abundant of the characteristic fungal compounds identified (Tabata *et al.,* 2011). Olfactometer bioassay of powdery mildew affected barley plants evoked a positive behavioral response in *C. septumpunctata* compared to the odor of uninfected controls (Radonjic *et al.,* 2018).

Fungus as nutrition to coccinellids

Fungus is a highly nutritious food source for many entomophagous coccinellids and fungal specialists. The most abundant constituent in most fungal tissues is water (85% by weight) except spores. Carbohydrates and proteins in fungi are the abundant source for the insect growth and development. Lipids, sterols, vitamins and other inorganic compounds of the fungi are also utilized by these insects (Mueller *et al*., 2001; Chang and Miles, 2004). However, the entomphagous coccinellids when fed alone with fungus may be lethal for their survival as they lack the digestive enzymes required for the digestion of cellulose and lignin and are unable to acquire sufficient nutrition (Lundgren, 2009). Fungus when fed as mixed diet along with aphids can increase their survival rate. In *C. septumpunctata*, 56% mortality was observed when fed with fungus alone on third day while the survival increased to 80% when fed along with aphids on sixth day (Radonjic *et al*., 2018).

Fungal Benefits from coccinellids

Mycophagous coccinellids aid in the mechanical transmission of fungus. Adherence of fungal strands and spores to the body of coccinellids aid in their dispersal. It's also worth noting that being eaten by coccinellid isn't always fatal for spores as they pass undigested due to lack of sufficient digestive enzymes and acts as vector for transmission. *Hippodamia convergens* carry the spores of the fungal pathogen, *Discula destructive* on their bodies and also consumes the fungus, thereby the spores are passed in their frass infecting new hosts (Colby *et al*., 1995, 1996; Hed *et al*., 1999). However, the coccinellids of Halyziini use powdery mildew fungi as a nutritive source and thought to be digested (Sutherland and Parrella, 2009).

Feeding potential of mycophagous coccinellids

The obligate mycophagous coccinellids have a great potential in the control of powdery mildew diseases. A handful of studies were carried out on the feeding potential of various mycophagous coccinellids in different crops speculating the possible utilization of these biocontrol agents in the control of powdery mildew diseases. *Psyllobora bisoctonotata* grubs cleared 92 per cent of the conidial density of *Erysiphe cichoracearum* infested okra leaves when fed to the beetles (Soylu and Yigit, 2002). The efficiency of *I. cincta* and *I. bistigmosa* was evaluated against the fungus *Phyllactinia corylea* causing powdery mildew in mulberry, where the infection decreased with the release of 5 pairs of adults per each plant. In addition, the beetles were efficient in controlling the disease when compared to fungicides (Krishnakumar and Maheswari, 2004). Sutherland and Parrella (2006), used a linear model to determine the consumption of powdery mildew by a single larva of *Psyllobora vigintimaculata*, where the model estimated that an average larva was able to clean 6.32 ± 3.3 cm^2 of leaf area of spores and hyphae during its development. The observations of Illahi *et al*. (2011) indicated that the five beetles of *Halyzia tschitscherini* have the potential to consume 96.40 cm^2 of powdery mildew infection in mulberry within 60 hours. Thite *et al*. (2013) reported the incidence of *I. cincta* on powdery mildew of *Dalbergia sisso* and *Xanthium strumarium* and also found that the larval stages were more voracious feeders of powdery mildew anamorphs than adult beetles. The strong association of powdery mildew of sunflower and the occurance of *I. cincta* has been established as the severity of disease incidence increased in India (Jagadish *et al*., 2006). The feeding potential of *I. cincta* was evaluated against *Erysiphe cichoracearum* causing powdery mildew of sunflower (Dharshini and Jagadish, 2018). Adult and third instar are the efficient feeders where they were able to clear mycelial area upto 4-8cm^2 within 36-48 hrs. Thus, by considering the feeding potentiality of adults and grubs of mycophagous coccinellids, the beetles may be employed effectively in biological control of powdery mildew diseases.

Sutherland *et al*. (2010) evaluated the effect of five fungicides used in grape vineyards of California and biocontrol agents *Bacillus subtilis*, *Stretomyces lydicus* on *P. vigintimaculata* under laboratory and field conditions where fungicides like wettable sulfur, trifloxystrobin and myclobutanil showed significant mortality in both the adults and larvae of the insect while the biocontrol agents proved to be nontoxic. Choudhury *et al*. (2020) reported the tritrophic movement of the systemic insecticide (imidacloprid) from the roots of a treated plant, into a plant pathogenic fungus, and these proved to be lethal to the mycophagous beetles when consumed. Various pesticides used in the cucumber cultivation of Korea for the control of pests are found to be toxic to the *I. koebele* which is a widely distributed and potential biocontrol agent against powdery mildew diseases in Korea (Lee *et al*., 2017). These pesticides also affected the pupation rate and fecundity of the adults. Hence, it is important to consider the effects of pesticide applications on mycophagous coccinellids to promote their utility in potential biological control of fungal diseases.

Considering the rapid spread of the disease and profuse sporulation of powdery mildew fungi, biological control using Halyziini alone may not be adequate for intensive agriculture. It may be possible to integrate these mycophagous coccinellids involving augmentation and conservation of these natural enemies along with the usage of compatible and safe fungicides and adopting cultural practices to control disease as part of an integrated disease management (IDM) program.

Conclusion

Mycophagy has evolved as a feeding transition in coccinellids. Fungi are consumed as a part of non- prey foods or as primary foods. Members of Halyziini have special morphological adaptations to rely on fungal feeding. Although numerous instances of fungal feeding in coccinellids are reported, still a deeper understanding is required in many aspects such as nutritional ecology, phylogenetics, mechanical transmission, chemical ecology and in particular, the possible utilization of the coccinellids for the biological control of fungal diseases.

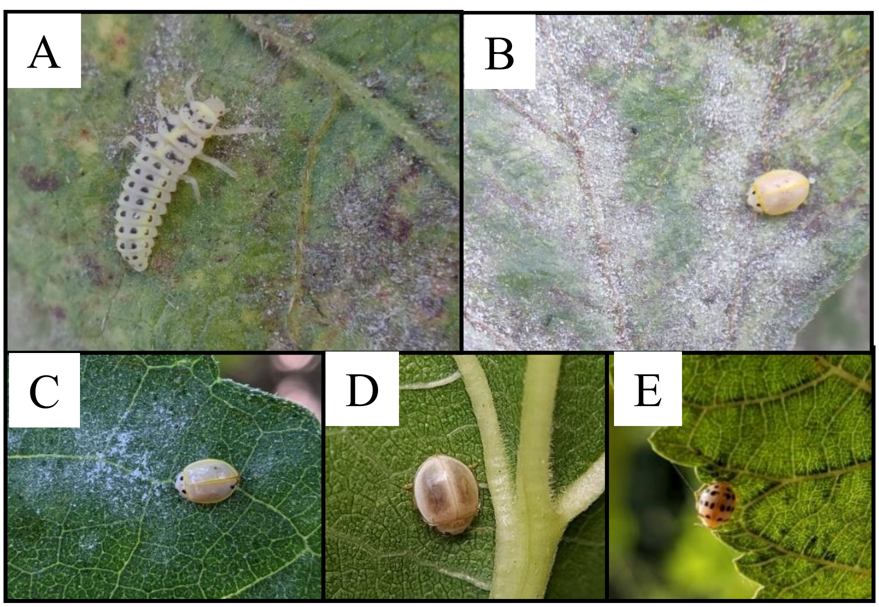

Fig. 1: A) Grub and B) Adult of *Illies cincta* feeding on powdery mildew of green gram and C) sunflower D) Adult of *Illies* sp. and F) *Psyllobara* sp. in mulberry

Reference

Caltagirone, L. E. and Doutt, R. L. 1989. The history of the Vedalia Beetle importation into California and its impact on the development of biological control. *Annual Review of Entomology*. **34**: 1–16.

Chang, S. T and Miles, P. G. 2004. Mushrooms: cultivation, nutritional value, medicinal effect, and environmental impact. CRC Press, Boca Raton, FL.

Choudhury, R. A., Sutherland, A. M., Hengel, M. J., Parrella, M. P. and Gubler, W. D. 2020. Imidacloprid movement into fungal conidia is lethal to mycophagous beetles. *Insects*. **11**(8): 496.

Colby, D. M., Windham, M. T and Grant, J. F. 1995. *Hippodamia convergens* (Coleoptera: Coccinellidae) dissemination of dogwood anthracnose fungus (Melanconiales: Melanconeacae). *Environmental entomology*. **24**(5): 1075-1079.

Colby, D. M., Windham, M. T., and Grant, J. F. 1996. Transportation and viability of conidia of *Discula destructiva* on *Hippodamia convergens*. *Plant Disease*. **80**: 804-805.

Crowson, R. A. 1981. The Biology of Coleoptera. New York, Academic Press.

Culik, M. P., Ventura, J. A., de Almeida, L. M., and Corrêa, G. H. 2011. Feeding by the coccinellid *Psyllobora rufosignata* (Coleoptera: Coccinellidae) on the Asian grapevine leaf rust fungus *Phakopsora euvitis* (Basidiomycota: Uredinales). *Biocontrol Science and Technology*. **21**(2): 235-238.

Del Pino, D., Olalla, L., Canovas, I., Cazorla, F. M., Devicente, A and Tores, J. A. 1999. Resistance to fungicides of *Sphaerotheca fuliginea* strains isolated from southern Spain. In: *Proceedings of the First International Powdery Mildew Conference*. **29:** 42.

Dharshini, G. M and Jagadish, K. S. 2018. Lifecycle and Feeding Potential of Mycophagous Coccinellid Beetle, *Illeis cincta* Fab. (Coleoptera: Coccinellidae) on Powdery Mildew Fungus, *Erysiphe cichoracearum* DC in Sunflower. *International journal of current microbiology and applied science*. Special issue **6:**1659-1675

Forbes, S. A. 1881. Notes on insectivorous Coleoptera. *Bulletin of the Illinois State Laboratory of Natural History*. **1**: 153–160.

Forbes, S. A. 1883. The food relations of the Carabidae and Coccinellidae. *Bulletin of the Illinois State Laboratory of Natural* History. **3**: 33–64.

Giorgi, J. A., Vandenberg, N. J., McHugh, J. V., Forrester, J. A., Ślipiński, S. A., Miller, K. B., Shapiro, L. R. and Whiting. 2009. The evolution of food preferences in Coccinellidae. *Biological Control*. **51**: 215–231.

Gubler, W. D., Ypema, H. L., Ouimette, D. G. and Bettiga, L. J. 1996. Occurrence and development of resistance in *Uncinula necator* to triadimefon, myclobutanil and fenarimol in California grapevines. *Plant Disease*, **80** (8): 902-909.

Heaney, S. P., Hall, A. A., Davies, S. A. and Olaya, G. 2000. Resistance to fungicides in the QoI-STAR cross resistance group: Current perspectives. In *The BCPC Conference: Pests and diseases, Volume 2. Proceedings of an international conference held at the Brighton Hilton Metropole Hotel, Brighton, UK, 13-16 November 2000* (pp. 755-762).

Hed, B. E., Windham, M. T and Grant, J. F. 1999. Survival of conidia of *Discula destructiva* in frass of the convergent lady beetle. *Plant Disease*. **83**: 806–809.

Illahi, I., Khan, M. A., Zeya, S. B., Aslam, M., and Mittal, V. 2011. Feeding potential of a mycophagous beetle *Halyzia tschitscherini* (Coleoptera: Coccinellidae) against powdery mildew *Phyllactinia corylea* in mulberry. *Indian Phytopathology*. **64** (2): 140-143.

Jagadish, K. S., Karuna K., Pankaja N. S., Nagaraju and Shadakshari, Y. G. 2006. Ladybird predator, *Illeis cincta* (Fabricius) (Coleoptera Coccinellidae) in relation to powdery mildew infection in Sunflower, *Helianthus annuus* L. *Insect Environment*. **12**(3): 124-125.

Kovar, I. 1996. Morphology and anatomy. In: Hodek, I. and Honěk, A. (Eds.), *Ecology of Coccinellidae*. Kluwer Academic Publishers, Netherlands, pp. 1–18.

Krishnakumar, R. and Maheswari, P. 2004. Management of powdery mildew in mulberry using coccinellid beetles, *Illeis cincta* (Fabricius) and *Illeis bistigmosa* (Mulsant). *Journal of Entomological Research*. **28**: 241–246.

Lawrence, J. F. 1989. Mycophagy in the coleoptera. In: Wilding, N., Collins, N. M., Hammond, P. M. and Webber, J. F. (Eds.), *Insect–Fungus Interactions*. 14th symposium of the Royal Entomological Society of London in collaboration with the British Mycological Society. Academic Press, London, pp. 2–23.

Lawrence, J.F. and Hlavac, T. 1979. Review of the Derodontidae (Coleoptera: Polyphaga) with new species from North America and Chile. *Coleopterists Bulletin*. **33**, 369– 414.

Lee, Y. S., Jang, M. J., Lee, H. A. and Lee, J. H. 2017. Toxicity of pesticides to mycophagous ladybrid, *Illeis koebelei* Timberlake (Coleoptera: Coccinellidae: Halyziini). *The Korean Journal of Pesticide Science*. **21**(4): 364-372.

Leschen, R. A. B. 2000. Beetles feeding on bugs (Coleoptera, Hemiptera): repeated shifts from mycophagous ancestors. *Invertebrate Taxonomy*. **14**: 917–929.

Lundgren, J. G. 2009. Relationship of natural enemies and non-prey foods. Springer, Dordrecht.

McGrath, M. T. 2001. Fungicide resistance in cucurbit powdery mildew: Experiences and challenges. *Plant Disease*. **85**(3): 236-246.

Mueller, U. G., Schultz, T. R., Currie, C. R., Adams, R. M. and Malloch, D. 2001. The origin of the attine ant-fungus mutualism. *Quarterly Review of Biology*. **76**: 169–197.

Murrin, F. 1996. Fungi and insects. In *Human and animal relationships*. Springer, Berlin, Heidelberg, pp. 365-388.

Radonjic, A., Terenius, O. and Ninkovic, V. 2018. The phytopathogen powdery mildew affects food-searching behavior and survival of *Coccinella septempunctata*. *Arthropod-Plant Interactions*. **12** (5): 685–690.

Ricci, C. 1982. Sulla costituzione e funyione delle mandibole delle larve di Tytthaspis sedecimpunctata (L.) e Tytthaspis trilineata (Weise). *Frustula Entomologica*. **3**: 205–212.

Samways, M. J., Osborn, R. and Saunders, T. L. 1997. Mandible form relative to the main food type in ladybirds (Coleoptera: Coccinellidae). *Biocontrol Science and Technology*. **7**: 275–286.

Sasaji, H. 1968. Phylogeny of the family Coccinellidae (Coleoptera). *Etizenia*. **35**: 1–37.

Ślipiński, A and Tomaszewska, W. 2010. Coccinellidae Latreille 1802. In: Leschen, R.A.B., Beutel, R.G. and Lawrence J.F. (Eds.), *Handbook of Zoology*. Vol. 2., Coleoptera, Walter de Gruyter GmbH & Co. KG, Berlin/New York, pp. 454–72.

Soylu, S and Yigit, A. 2002. Feeding of mycophagous ladybird, *Psyllobora bisoctonotata* (Muls.) on powdery mildew infested plants. *International Organization for Biological Control Western Palearctic Regional Section Bulletin*. **25** (10): 183–186.

Sutherland, A. M and Parrella, M. P. 2006. Quantification of powdery mildew consumption by a native coccinellid: implications for biological control. In: Hoddle, M. S. and Johnson, M.W. (Eds.), *California Conference on Biological Control* 5 (Riverside). Proceedings, pp. 188–192.

Sutherland, A. M and Parrella, M. P. 2009. Mycophagy in Coccinellidae: review and synthesis. *Biological Control*. **51**(2): 284-293.

Sutherland, A. M., Gubler, W. D and Parrella, M. P. 2010. Effects of fungicides on a mycophagous coccinellid may represent integration failure in disease management. *Biological Control*. **54** (3): 292-299.

Tabata, J., De Moraes, C. M and Mescher, M. C. 2011. Olfactory cues from plants infected by powdery mildew guide foraging by a mycophagous ladybird beetle. *PLoS One*, **6**(8): e23799.

Thite, S. V., Chavan, Y. R., Aparadh, V. T and Kore, B. A. 2013. Incidence of *Illeis cincta* (Fabricius) on powdery mildew of *Dalbergia sisso* and *Xanthium strumarium*. *International Journal of Advanced Research*. **1**: 20-23.

Thomas, M. C. 1993. A new species of *Cryptolestes* Ganglbauer from the Middle East and a new synonym (Coleoptera: Laemophloeidae [Cucujidae sensu lato]). *Israel Journal of Entomology*. **27**: 113–118.

Triltsch, H. 1997. Gut contents in field sampled adults of *Coccinella septempunctata* (Col.: Cocinellidae). *Entomophaga*. **42**: 125–131.

Turian, G. 1969. Coccinelles micromycetophages (Col.). *Bulletin de la société entomologique suisse*. **42**: 52–57.

Vandenberg, N. J., 2002. Family 93. Coccinellidae Latreille 1807. In: Arnett, R.H. Jr., Thomas, M.C., Skelley, P.E., Frank, J.H. (Eds.), American Beetles. Polyphaga: Scarabaeoidea through Curculionoidea, Vol. 2., CRC Press LLC, Boca Raton, FL, pp. 371–389.

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