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TIME TO RESTART: STUDY OF THE DERMAPTERA OF THE INDIAN SUBCONTINENT

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ABSTRACT

The Dermaptera is a polyneopteran order with > 2,000 described species from mainly tropical, subtropical, and warm temperate regions. More than 310 species of the Dermaptera belonging to nine families have been reported from the Indian subcontinent (India, Pakistan, Nepal, Bhutan, Bangladesh and Sri Lanka) as a result of the extensive work of Gyanendra Kumar Srivastava. Embracing environmental and climatic heterogeneity, the Indian subcontinent is an intersection of multiple faunal regions and includes several dermapteran groups of special interest. To restart the studies on the Dermaptera of this region, which has been stagnant for a decade, this paper includes a beginner's guide for collecting and identifying Dermaptera, together with a brief summary of recent advances in their classification and phylogeny.

Key words: Dermaptera, classification, collection, earwigs, India, ecology, distribution, genitalia, identification, regional fauna characteristics, alpha taxomoy, DNA barcoding, recent advances

Dermaptera is a polyneopteran order with >2,000 described species from mainly tropical, subtropical, and warm temperate regions (Popham 2000; Grimaldi and Engel, 2005; Zhang, 2013; Haas, 2018; Hopkins et al., 2018). The insects of this order, commonly known as earwigs, are characterized by their sclerotized, unsegmented forceps at the caudal end of the abdomen, which are specialized cerci (Fig. 1A-C). Forceps are used in defence to enemies (Eisner, 1960), predation (Jiang and Kajimura, 2020), and opening of wings (Kleinow, 1966; Haas, 2003). Adult forceps are usually sexually dimorphic, and used in male-male competition for mates and courtship displays (Briceño and Eberhard, 1995; Kamimura, 2014). Most of the species of the Dermaptera are either omnivorous or carnivorous insects that live in diverse natural and semi-natural environments (Günther and Herter, 1974; Renz and Kevan, 1991). Several species are considered nuisance organisms or pests in either horticultural or agricultural contexts; for example, *Nala lividipes* (Dufour) (Labiduridae) is known to a pest of beetroot seedlings (Cooper, 1992), and *Euborellia cincticollis* (Gerstaeker) (Anisolabididae) damage seedlings and mature fruit of muskmelons (Knabke and Grigarick, 1971). On the other hand, some other species could be useful as biological control agents. For example, *Labidura riparia* (Pallas), a cosmopolitan species of Labiduridae, is known to be predaceous on many insects including lepidopteran larvae (Schlinger et al., 1959; Tawfik et al., 1972). Nishikawa et al. (2006) reported that *Chelisoches variegatus* (Burr) (Chelisochidae) eat *Brontispa longissima* (Gestro) (coconut leaf beetle) in coconut fields. However, a vast majority of the species of Dermaptera are considered to have no direct relationships with human activities. Accordingly, the basic bionomics have been studied for only a few of the more common species. Little published information on the ecology of most species is currently available (Günther and Herter, 1974; Renz and Kevan, 1991; Costa, 2006; Haas, 2018), irrespective of their potential, hitherto unknown ecosystem functions in natural and agricultural environments: recent studies have revealed that *Doru luteipes* Scudder, a predatory Forficulidae, is attracted to herbivore-induced plant volatiles (Naranjo-Guevara et al., 2017) and termitophily of *Spirolabia kaja* Kočárek (Spongiphoridae) in a dipterocarp rain forest in Borneo (Kočárek and Wahab, 2021).

Engel and Haas (2007) revised the hierarchical classification and family-group names of living and extinct Dermaptera. Their system and subsequent modification by Engel et al. (2017) classify extant Dermaptera species into 12 families in two infraorders: Protodermaptera: Karschiellidae, Diplatyidae, Pygidicranidae and Haplodiplatyidae; Epidermaptera: Hemimeridae, Apachyidae, Anisolabididae

(= Carcinopholidae), Labiduridae, Arixeniidae, Spongiphoridae (= Labiidae), Chelisochidae and Forficulidae. Representatives of nine of these families are known from the Indian subcontinent viz. the Republic of India and adjacent countries (Pakistan, Nepal, Bhutan, Bangladesh, and Sri Lanka) (Srivastava, 2013): exceptions being Karschiellidae that are possible ant predators in the Ethiopian region (Hincks, 1959), Hemimeridae that live phoretically on the giant pouched rats (*Cricetomys* Waterhouse spp.) in Africa (Nakata and Maa, 1974), and Arixeniidae that are associated with bat (*Cheiromeles torquatus* Horsfield) roosts in the Oriental tropics (Nakata and Maa, 1974).

In the extant Dermaptera, males of Apachyidae, Labiduridae, Anisolabididae, Pygidicranidae, Diplatyidae, Haplodiplatyidae and Karschiellidae usually have laterally paired penises (Fig. 1E, E', E''): but the left penis is largely reduced and vestigial in Karschiellidae (Steinmann, 1986), whereas only a single penis is present in Spongiphoridae, Chelisochidae, Forficulidae, Arixeniidae and Hemimeridae (Fig. 1F, F'; Burr, 1915a, b; Popham, 1965; Kamimura, 2014). A single virga, a sclerotised tube with a species-specific shape, which constitutes the terminal part of the ejaculatory duct, is enclosed in the membranous penis lobe (Fig. 1E, F). The phylogenetic relationships among the families are still largely unsettled, possibly due to difficulty in rooting the Dermaptera by a sister order. Several studies based on the morphological and/or molecular datasets suggested that monophyletic or paraphyletic Protodermaptera consists of the basal offshoot(s), with (Haas, 1995; Haas and Kukalová-Peck, 2001) or without (Jarvis et al., 2005; Kočárek et al., 2013; Naegle et al., 2016) monophyly of the families with a single penis (Nanorder Eudermaptera plus Hemimeridae). However, some recent studies suggest that Apachyidae is the sister group to the remaining Dermaptera (Wipfler et al., 2020; Chen, 2022).

Alpha taxonomy provides the basis for all other disciplines of biology, including biogeography and applications in agriculture such as biological control programmes. Most of our knowledge of the α-taxonomy of the Dermaptera of the Indian subcontinent is due to the work of Gyanendra Kumar Srivastava of the

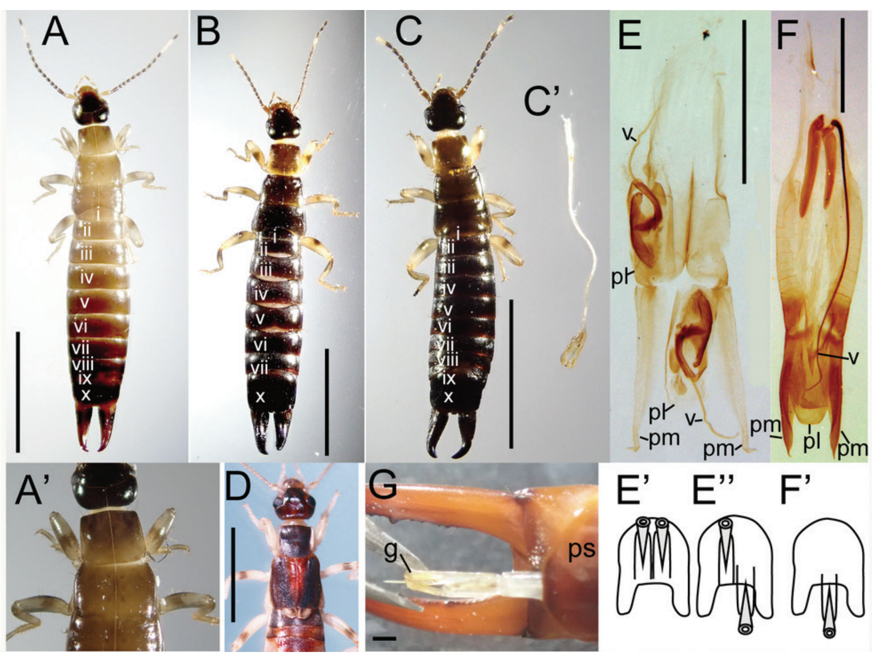

Fig. 1. A last-instar nymph (A), adult female (B), and adult male (C) with his genitalia extracted from the body (C') of *Euborellia annulipes* (Lucas), an apterous species of Anisolabididae. An enlarged view of A shows thoracic ecdysial lines (A'). Head and thorax of male *Labidura riparia* (Pallas) with the fully developed tegmina and wings (D). Male genitalia of *Epilandex burri* (Borelli) (Anisolabididae) (E) and *Adiathella tenebrator* (Kirby) (Chelisochidae) (F) with schematic drawings of male genitalia with two penises (E', E'') and one penis (F'). Male genitalia of *L. riparia* extracted from the genitalia chamber (the space above the penultimate sternite) with fine forceps (G). Roman numerals indicate the abdominal sternites I-X. Abbreviations: g, male genitalia; pl, penis lobe; pm, paramere; ps, penultimate abdominal sternite; v, virga. Scale bars: 1 cm in A-C; 5 mm in D; 1 mm in E-G.

Zoological Survey of India, who published >120 papers and notes on the Dermaptera of India and other countries. In his Fauna of India and the adjacent Countries, Dermaptera, he has reported >310 species (Srivastava, 1988; 2003a; 2013), corresponding to *c*. 16% of the Dermaptera worldwide. Obviously, the extensive studies by Srivastava resulted in the knowledge of stunning species diversity, which is relating to the climatic and environmental heterogeneity of the Indian subcontinent as discussed below. However, the study of the Dermaptera of the Indian subcontinent had stalled in the last decade.

Characteristics of the dermapteran fauna of the Indian subcontinent

The cerci of adult Dermaptera are always present as unsegmented forceps. However, segmented cerci are known in the nymphal stages of Haplodiplatyidae (Bormans and Krauss, 1900), Diplatyidae (Shimizu and Machida, 2011b) and Karschiellidae (at least in the distal part; Haas et al., 2012), supporting the view that these families represent the earliest offshoots of extant Dermaptera (Haas and Klass, 2003). Among them, *Haplodiplatys* Hincks, which comprises the monotypic family Haplodiplatyidae (Engel et al., 2017), is of special interest being characterized by multiple plesiomorphic features, including the laterally symmetrical tegmina and absence of a spiny ridge (a component of the tegmina-locking device) on the dorsal side of the mesothorax (Haas and Kukalová-Peck, 2001). Among the 36 species known in *Haplodiplatys* (Hopkins et al., 2018: accessed 25 July 2022), 16 species (plus another four described by Srivastava in 1988) have been reported from the Indian subcontinent (Srivastava, 2013). Majority of them are more common in forested slopes of Himalaya, but *H. stemmleri* Brindle, is sometimes found at higher elevation up to 3100 masl (Srivastava, 1988). Strikingly contrasting to the distribution of *Haplodiplatys*, the diversity of *Diplatys* Audinet-Serville (Diplatyidae) is the greatest in peninsular India (Karthik et al., 2022). These examples indicate the relevance of environmental heterogeneity in the Indian subcontinent, from alpine to lowland tropical, as the cause of the total diversity in this region. Similarly, many Forficulidae (e.g., *Eudohrnia* Burr, *Liparura* Burr and *Anechura* Scudder) have Palaearctic distributions and are confined to the northern part of the Indian subcontinent, while Chelisochidae is a tropical-subtropical element (Srivastava, 1988; 2013), consistent with their general global trends (Popham, 2000).

The generic diversity of Anisolabididae strongly supports the view that the Indian subcontinent is an intersection of multiple faunal regions. The occurrence of some genera on the Indian subcontinent, such as *Titanolabis* Burr and *Epilandex* Hebard indicates the affinity to the Oriental-Australian regions (Srivastava 2003a). On the other hand, six species of *Aborolabis* Srivastava have been recorded from northeast India, Nepal and Bhutan, while others are known from the Iberian Peninsula to North Africa (Srivastava, 1993b; 2003a). In Anisolabididae of Srivastava (1999; 2003a; 2013), the Isolaboidinae, recorded only from India to Anatolia, is of special interest because of its unique morphology and the controversy about its phylogenetic placement. The males of Isolaboidinae possess unique genitalia with a single, well-developed penis and a conspicuous spirally-coiled virga (Brindle, 1978; Steinmann, 1989a; Srivastava, 1996; 2003a). Although many authors place Isolaboidinae under Spongiphoridae (Steinmann, 1989a, b; Engel and Haas, 2007), males of which possess only a single penis (see above), Srivastava (1996) argued that the right penis lobe (= distal lobe) is atrophied either with or without rudimentary virga, whereas the left penis is developed with a spirally coiled virga in the Isolaboidinae. Accordingly, Srivastava (1996; 1999; 2003a; 2013) placed Isolaboidinae in Anisolabididae, which is characterized by laterally paired penises. Studies indicate that the left penis is atrophied in the ancestor(s) of Eudermaptera (including Spongiphoridae) (Popham, 1965; Kamimura, 2006; 2007). Accordingly, the evolutionary loss of the right penis in Isolaboidinae should have occurred independently to instances of left-side reduction. To resolve this controversy, future studies must examine the phylogenetic placement, development and reproductive biology of Isolaboidinae.

The 'Zoogeography' section in Srivastava (1988) provides additional details on the generic compositions of the Dermaptera of the Indian subcontinent. His contributions go far beyond the α-taxonomy of the Dermaptera and generic and suprageneric classifications proposed by him (Pygidicranidae and Diplatyidae, Srivastava, 1993a; Anisolabididae, Srivastava, 1999; Spongiphoridae, Srivastava, 1995; and Chelisochidae, Srivastava, 2003b) are important references for understanding the evolution of the Dermaptera.

How to study the taxonomy and basic ecology of Dermaptera

The Dermaptera occurs in diverse environments: under barks of living or dead trees in natural and secondary forests; under rocks along streams; associated with marine litter; associated with dungs (fumicolous); or in agricultural fields or insect-induced galls. Some species of *Forcipula* Boliver and *Nala* Zacher (Labiduridae) are almost semi-aquatic (e.g., Julka and Purohit, 1983). Hand sorting with a shovel (and with an aspirator for smaller taxa) is usually the most efficient way to collect them. For some species, pitfall traps with various baits (Núñez-Bazán et al., 2022) or light traps (Girod and Matzke, 2020) are also effective.

It is usually difficult to identify the Dermaptera to the species level based only on nymphs. As in other hemimetabolous insects lacking a pupal stage, dermapteran nymphs resemble adults (Fig. 1A-C). Adults can be distinguished from nymphs by the presence of tegmina (= forewings) and wings (= hindwings): the latter are folded under the tegmina when in repose (Fig. 1D: Haas et al., 2000; Saito et al., 2020). In some species, both the tegmina and wings are totally absent (Fig. 1 A-C). Even in such species, nymphs can be distinguished from adults by their thin exoskeleton with the ecdysial line (Fig. 1A'). As in many other insect groups, adult female Dermaptera are usually more difficult to identify to species than adult males. Rearing females (and nymphs) in the laboratory is one way of identifying them. Wild-caught females frequently possess sperm in the spermatheca (an internal organ for sperm storage) and lay fertilized eggs under rearing conditions. All the Dermaptera studied to date show varying degrees of maternal care of the offspring [Costa 2006; but see Shimizu and Machida, 2011a for a possible exception in *Apachyus chartaceus* (de Haan) (Apachyidae)]. By this, one can also study their reproductive biology (Matzke and Klass, 2005; Kamimura et al., 2016; Kočárek and Wahab, 2021), and obtain laboratory-reared adults for additional taxonomic, morphological, developmental, and molecular studies. Bhaskara Narasurama Ramamurthi of Loyola College (Tamil Nadu), one of the pioneers of dermapteran taxonomy of India, also studied the development of male genital systems of several groups, and the ovoviviparity of *Marava arachidis* (Yersin) by means of rearing (Ramamurthi, 1956; 1958).

Animal genitalia used for copulation and sperm transfer, especially those of males, are often more complex than is necessary for sperm transfer alone and seem to evolve more rapidly than other structures (Eberhard, 1985; Hosken and Stockley, 2004). Since males voraciously pursue mating while females avoid mating, sexual conflict over mating can result in antagonistic coevolution of genitalia (Arnqvist and Rowe, 1995; 2002; Kokko and Jennions, 2014). For species that are potentially polygamous, post-copulatory sexual selection can also promote genital coevolution between the sexes (Eberhard, 1985; 1996). This is also true for Dermaptera (Kamimura, 2014). For example, male *M. arachidis* possess a pair of sclerites in the penis lobe, which forcibly pinch the genital region of the female mates during copulation, resulting in copulatory wounds (Kamimura, et al., 2016). Male *Euborellia* spp., are known to use the elongated genitalia to remove rival sperm from the tubular spermatheca of the mates (Kamimura, 2000; van Lieshout and Elgar, 2011). Accordingly, the identification of closely related species often requires an examination of the genital morphology by specialist taxonomists. Contemporary descriptions of new species of Dermaptera include detailed illustrations of male genitalia, and the description of a new species based only on nymphal and/or female specimens is not recommended (particularly when intraspecific morphological variations are not clarified).

In adult males, 10 abdominal segments are observable from the dorsal side, as in nymphs of both sexes. The 8th and 9th abdominal segments of adult females are largely reduced and invisible from the dorsal side (Fig. 1 A-C). From fresh or soft alcohol-preserved material (or specimens stored in a freezer at <20°C for a short period before desiccation of the body), it is easy to remove the genitalia from the male dermapteran body compared with other insect groups. By gently lifting the penultimate sternite under a stereomicroscope, one can directly see and grasp the main part of the male genitalia with fine forceps (Fig. 1G). Carefully pulling them from the body, the genitalia can be removed without damaging other body parts. In some species (especially many Anisolabididae), however, the male genitalia are very elongate (Fig. 1C, C') and extra caution is required to not tear them during extraction. To remove the male genitalia from dry or hard specimens, because of storage in >80% ethanol, the whole body must first be softened in hot water. In many Dermaptera, sclerites or denticulated pads also develop on the penis lobe. To observe these structures in detail, the male genitalia can be treated in alkaline solution (usually 10% KOH) for clearing; this is sometimes indispensable for hardened samples preserved in ethanol. The shapes of the parameres (Fig. 1E, F) and those structures associated with penises are important for generic and specific diagnoses, as well as to observe the virgal morphology.

To identify the Dermaptera of the Indian subcontinent, "The Fauna of India and the Adjacent Countries: Dermaptera, Parts I–III" by Srivastava (1988; 2003a; 2013) is the most useful reference. Steinmann's (1986; 1989a; 1989b; 1990; 1993) monographs and catalogue, bibliographic compilations by Sakai (1985; 1987; 1990-1994; 1995a-d; 1996), and the website Dermaptera Species File (Hopkins et al., 2018) are also helpful. To identify closely related species, DNA barcoding is effective. The universal primer set, LCO1490 and HCO2198, which have been designed to amplify an approximately 700 base-pair region of the mitochondrial cytochrome oxidase subunit I (COI) gene (Folmer et al., 1994), usually works well in most of the extant dermapteran taxa (Stuart et al., 2019; Kalaentzis et al., 2021; Kočárek and Wahab, 2021; Y K, unpublished data). Ethyl acetate vapour is often used to kill insect samples including Dermaptera to avoid subsequent rotting and hardening of the body. However, it causes serious DNA degradation and can hamper subsequent molecular analyses (Dillon et al., 1996). A recent study demonstrated that propylene glycol can be a promising preservative comparable to ethanol for PCR-based studies (Nakamura et al., 2020).

Possibly due to increased freight traffic, some of species have been reported to have expanded their distributions. For example, Nishikawa and Naka (2019) reported *Paradiplatys gladiator* (Burr) (Diplatyidae) from a port in Japan, and considered it was incidentally introduced from India. For researchers outside India, it is sometimes difficult to detect and examine the type material of species described from India and adjacent countries. As recommended in Recommendation 16C of the International Code of Zoological Nomenclature (fourth edition, 1999) "authors should deposit type specimens in an institution that maintains a research collection, with proper facilities for preserving them and making them accessible for study". Photographic databases of museum specimens, especially those of name-bearing types, are also warranted to accelerate studies of Dermaptera, so that we can catch up with accelerating changes in global environments. The fauna of the Indian subcontinent is also changing. In 2018, *Spodoptera frugiperda* (J E Smith) (Lepidoptera: Noctuidae) invaded southern India, and a native Dermaptera species (*Forficula* sp.: possibly *F. gravelyi* Burr) is a possible natural enemy of *S. frugiperda* (Shylesha et al., 2018; Sharanabasappa et al., 2019). In addition, Karthik et al. (2022) discovered a new species of Diplatyidae, *Diplatys sahyadriensis* Karthik, Kamimura et Kalleshwaraswamy in a sugarcane field in Kartanaka. Although Srivastava published many faunal monographs for each Indian state or nature reserve, no comprehensive review has been published for southern India (Karnataka, Kerala, Andhra Pradesh, Tamil Nadu and Telangana states). Extensive faunal studies in what might be the most species-rich area of the Indian subcontinent will be important for furthering our understanding of the Dermaptera.

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