

# Comparative morphology of eight endemic *Arthrosphaera* (pill-millipedes) of the Western Ghats

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## ABSTRACT

The giant pill-millipedes (*Arthrosphaera*) are the most conspicuous megadiverse soil fauna and their population consists of 40 species dispersed in peninsular India. They are the most underexplored terrestrial invertebrates with meager morphological descriptions. This study embodies morphological features of eight species of *Arthrosphaera* from the Western Ghats of India by light microscopy and scanning electron microscopy. Species of the genus *Arthrosphaera* possess uniform external characteristics with variation in size and coloration. Morphological features have been assessed considering characteristics of eight major body parts (right antennae, gnathochilarium, anterior telopods, posterior telopods, male's 9<sup>th</sup> left leg pair, 2<sup>nd</sup> leg pair in males as well as females, washboard in females, and the endotergum of the 9<sup>th</sup> segment). The anterior and posterior telopods of males have prominent species-specific diagnostic features. The two stridulation ribs on the first podomere of anterior telopods are represented in six species (*Arthrosphaera carinata*, *A. dalyi*, *A. davisoni*, *A. fumosa*, *A. hendersoni* and *A. magna*), while single rib exists in two species (*A. distincta* and *A. versicolor*). The caudal end of females possesses a washboard, which helps in stridulation, an important mating behavior. In the present study in addition to morphological features, distribution, ecology and conservation strategies are discussed.

**Keywords:** *Arthrosphaera*, conservation, distribution, ecology, endemism, life history

## 1. INTRODUCTION

The lack of non-standardized nomenclature and insufficient application of molecular techniques made the field of myriapodology one of the neglected areas (Sierwald & Reft, 2004). The taxonomy of millipedes is historically biased owing to constraints in sampling and morphological description rely on a few available individuals (Wesener and Sierwald, 2005a). In spite of the highly diverse soil macrofauna in the Western Ghats, the diversity and distribution of millipedes are still fragmentary and in the exploratory stage (Rossi and Blanchart, 2005). Giant pill-millipedes belonging to Sphaerotheriida

are one of the most conspicuous invertebrates in the forest ecosystem of Western Ghats (Ashwini & Sridhar, 2008). The Indian Sphaerotheriida (genus *Arthrosphaera*) was proposed by Pocock (1899) and subsequently, Attems (1936) added additional species with general taxonomic descriptions. Owing to microendemic distribution, *Arthrosphaera* became one of the most understudied millipedes in peninsular India (Wesener & Sierwald, 2005a, Wesener et al., 2010). Major morphological studies on *Arthrosphaera* were performed more than a century ago (the 1890s) and there is an urgent need for revision of their fragmentary systematics (Wesener et al., 2010). Recently, Wesener and Sierwald (2005b) and Wesener et al. (2010) contributed significantly to the systematics of millipedes of Malagasy giant pill-millipedes of order Sphaerotheriida through extensive studies. The genus *Arthrosphaera* of the family Arthrosphaeridae currently consists of nearly 40 species mainly in Peninsular India (Wesener & VandenSpiegel, 2009).

The genus *Arthrosphaera* possesses a relatively uniform external appearance and characteristics. Their body consists of 13 tergites with a small laterally concave thoracic shield in the first tergite called collum and the caudal end of the body is covered with pygidium (Wesener & Sierwald, 2005a). Most of them are passive in movement and they never trust speed for escape from predators (Eisner & Davis, 1967). Individuals belonging to the genus *Arthrosphaera* are adapted for volvation (conglobation) into a perfectly spherical ball as a measure of defense against predation on disturbance and during the resting stage (Pocock, 1892). According to Eisner & Davis (1967), such conglobation behaviour is one of the strongest anti-predation systems that evolved in the animal kingdom. During volvation, the pygidium fixes into the concave lateral region of the thoracic shield to roll up and it fully covers the head and collum. Besides, the pygidium has special sclerotised locking carinae on its ventral part, that helps in locking itself from inside and all the vulnerable parts could be covered/protected under a heavily armored tergite cage.

The bisexual stridulation (stridulatory organs: males, telopods; females, washboard) is an important apomorphy in *Arthrosphaera*. These stridulating organs are unique to the pill-millipedes belonging to *Arthrosphaera*. The genus *Sphaeromimus* in Madagascar is closer to the genus *Arthrosphaera* in India compared to the other genera *Zoosphaerium* and *Microsphaerotherium* exits in Madagascar (Wesener & VandenSpiegel, 2009). The giant pill-millipede fauna in the Madagascar has been considered a pre-Jurassic element and it was predicted that *Arthrosphaera* also evolved simultaneously with significant ecological roles during the Gondwanan period (Wesener & VandenSpiegel, 2009). However, the pill-millipedes are highly neglected soil fauna in many aspects of their morphology, diversity and cytology (Wesener et al., 2010). Hitherto, a few species have been described morphologically mainly based on light microscopic observations (Kadamannaya & Sridhar, 2009; Kadamannaya et al., 2012). The present study was carried out to unravel various morphological characters of eight species of *Arthrosphaera* found in the forest of the Western Ghats of India based on light microscopic as well as scanning electron microscopic (SEM) interpretations. Besides morphology, this study also contributes: i) male and female sexual characteristics; ii) intraspecies variations and life history strategies; iii) pattern of distribution and ecology.

## 2. MATERIALS AND METHODS

Eight adult species of *Arthrosphaera* (*A. carinata*, *A. davisoni*, *A. dalyi*, *A. disticta*, *A. fumosa*, *A. hendersoni*, *A. magna* and *A. versicolor*) were collected from different forests and plantations in the Western Ghats (Kadamannaya, 2008; Ambarish, 2014) were considered for detailed morphological analysis. Both male and female individuals of each species were sacrificed, cleaned and preserved in preservative (70% ethanol). Individuals of each species were dissected and separated the following body parts: right antennae, gnathochilarium, anterior telopods, posterior telopods, male's 9<sup>th</sup> left leg pair, 2<sup>nd</sup> leg pair in males as well as females, washboard in females, and the endotergum (lower side of posterior margin of tergites) of the segment 9.

The morphological features of different parts were deduced mainly based on scanning electron microscopy (SEM) with emphasis on male and female sexual characteristics. For SEM analysis, different parts were further cleaned in 70% ethanol followed by dehydration in ethanol (80%, 90%, 95% and twice in 100%) followed by overnight air-drying. Each part was mounted on stubs using sticky tabs, the stubs were sputter-coated with gold and observed under SEM (Joel, JSM 6380 LA, Japan). Snaps were taken by a Nikon D40 digital camera mounted onto a Stereomicroscope (Nikon, D40 USA). The terminology of morphological features of different parts was followed according to the recent literature by VandenSpiegel et al. (2002) and Wesener and Sierwald (2005b).

## 3. ABBREVIATIONS

The following abbreviations are used to denote specific characteristic features of different parts of pill-millipedes in the figures:

AM, Anterior margin

As, Anal shield

CA, Central area

CP, Central pads at the lingual lamella on gnathochilarium

cr-t, Crenulated teeth  
 cT, Comb teeth  
 Cx, Coxa  
 EP, Exterior plate of vulva  
 Go, Gonopores  
 IH, Inner horns  
 iP, Inner palpus  
 IP, Inner plate of vulva  
 LL, Lingual lamella  
 l-Sn, Large sclerotized nodules  
 m-br, Marginal bristles  
 ml, Membranous lobe  
 mp, Molar plate  
 O, Operculum of vulva  
 P, Palpi of gnathochilarium  
 S, Sternite  
 S-p, Sclerotised spots  
 S-pl, Sclerotised plates  
 SR, Stridulation ribs  
 s-se, Short setae  
 s-Sp, Short spines  
 Ts, Thoracic shield

## 4. DESCRIPTION

### 4.1. *Arthrosphaera carinata* Attems 1936 (Figure 1a and 1b)

**Locality:** Collected from mixed plantations in Adyanadka, foothill region of Western Ghats, Southern India (12°41'N, 75°6'E). Litter depth 2–3 cm and litter temperature 28°C. The specimens are preserved in the zoological museum of Mangalore University, Karnataka, India (MUAZPMAc-01).

**Diagnosis:** Length, up to 42 mm; width, 19 mm; weight, 10.8 g. Male is slightly bigger than female. The colour is shiny-black with a posterior deep-brown margin. The thoracic shield is black with a brown margin. Antennae are deep-green with more than 80 sensory cones at the apical disk. The anal tergite is slightly bell-shaped. Two well-developed black locking carinae are present on each side of the anal tergite as well as anterior one is double the length of the posterior one.

**Body length:** Holotype male length up to 49 mm and female up to 44 mm (n=16). Weight varies from 6.3–10.8 g. Breadth ranges from 16–23 mm. Male widest axis ranges from 21.3–29.2 mm and female 23.1–28.9 mm. The narrow axis of males varies from 18.3–26.6 mm and females ranges from 20.5–23.7 mm. Female is slightly smaller than male.

**Habitus:** Medium size animal, posterior margins are deep brown and tergite is finely punctured.

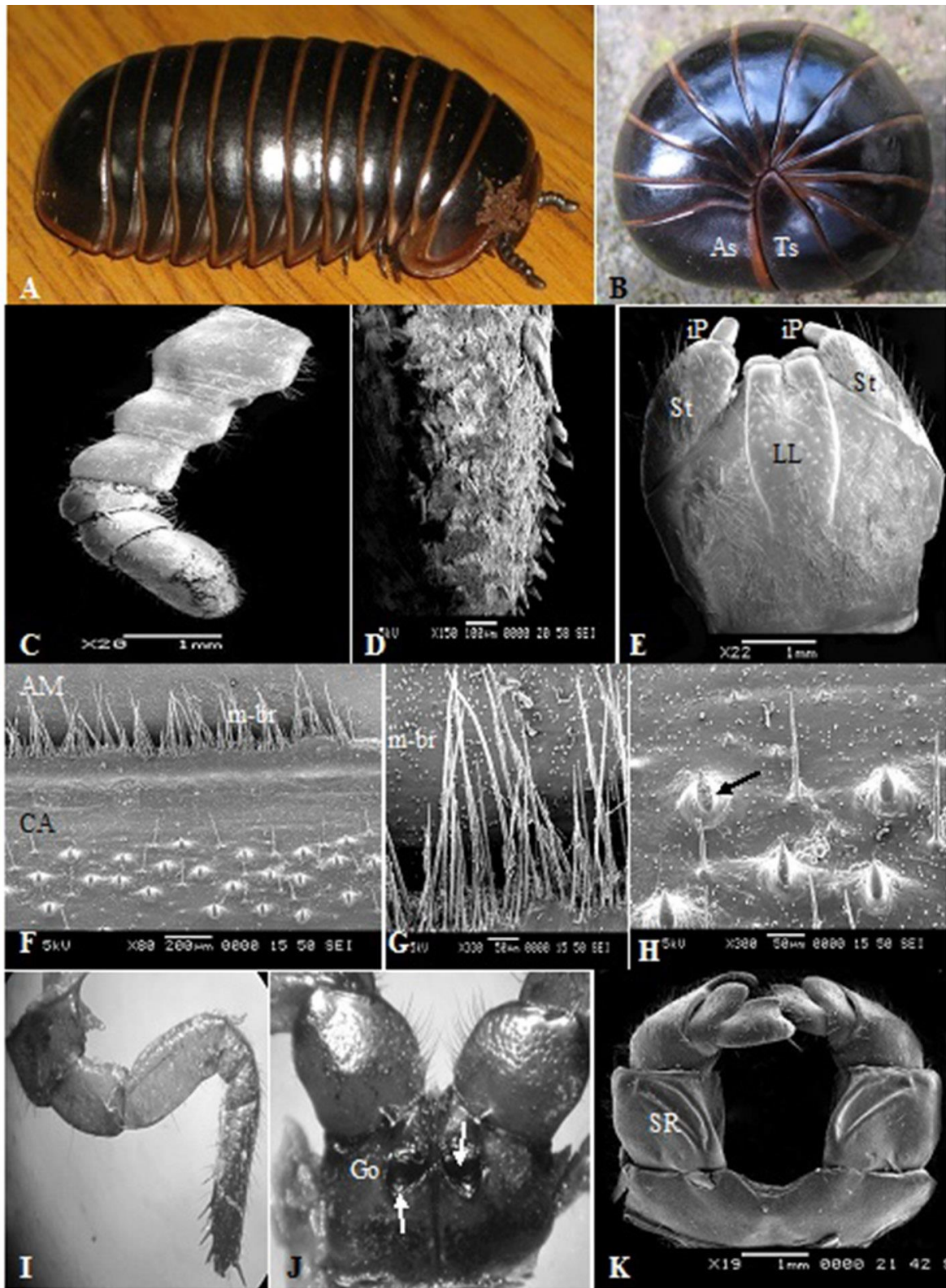
**Coloration:** Glabrous and shiny-black with a thin deep-brown posterior margin are conspicuous during movement and less clearly visible during conglobation. Collum black, head and antennae deep-green, legs pale-green and anal shield mimics tergites.

**Head:** Black, eyes with ~90–94 ocelli and possesses a few sclerotised spots. The socket of antennae possesses crenulated fine teeth. Long hairs are found at the posterior end and conspicuous tuft of bristle occupies the region towards the collum. Mouthparts were not dissected. Mandible possesses ~4–5 pectinate lamellae and the number of teeth of pectinate lamellae decreases from apical to proximal.

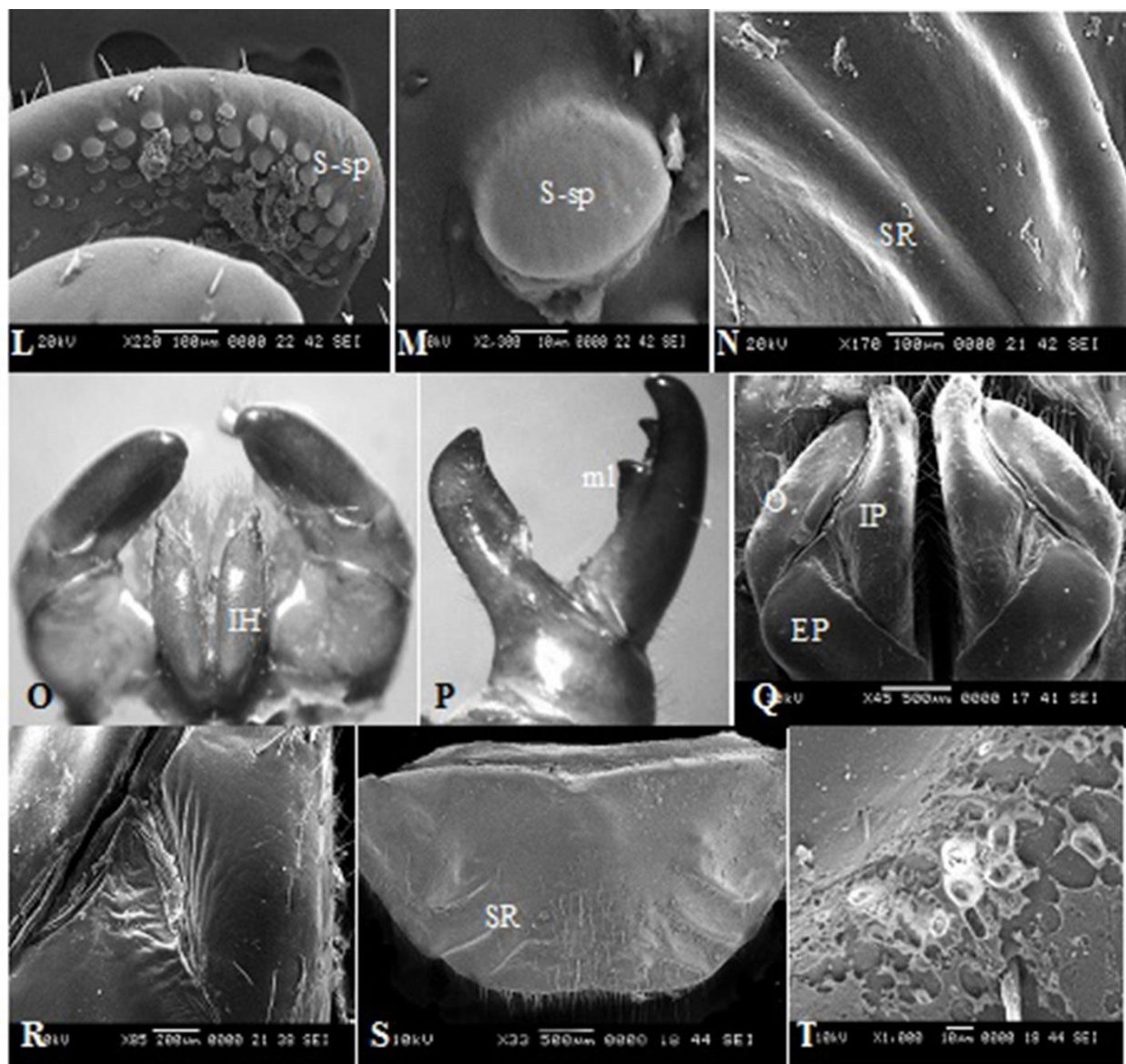
**Collum:** Single row of short hairs on the anterior edge and a few isolated long hairs on the posterior margins are clearly visible. The inner portion of the margins consists of a tuft of hairs.

**Thoracic shield:** Color mimics the tergite, a row of short hairs found on the anterior and posterior margin. Lateral extensions have numerous hairs. A dark-brown thickened region is found the opposite to the eyes. Height is ~12–13 mm and width is ~22–24 mm.

**Antennae:** Antenna is deep-green with six antennomeres. The first antennomere is broader than the remaining and possesses a few sclerotised spots. Length of antennomere: 1>2=3>4=5<6. The 6<sup>th</sup> antennomere is expanded, the oblique and the terminal disc consists of ~110 sensory cones.



**Figure 1a.** *Arthrosphaera carinata* Attems. **A**, moving animal; **B**, conglobated animal; **C**, right antenna; **D**, shoe-shaped last antennomere; **E**, gnathochilarium ventral side; **F**, endotergum overview; **G**, posterior margin, **H**, the internal area of endotergum (arrow, spine); **I**, leg. **Male sexual organs**: **J**, holotype of the second coxa with male gonopore (arrows); **K**, anterior telopods (anterior view).



**Figure 1b.** *Arthrosphaera carinata* Attems. **L**, sclerotised spots on podomere of anterior telopod; **M**, sclerotised spot; **N**, ribs on telopods (over view); **O**, posterior telopods (top view); **P**, right chela of posterior telopod. **Female sexual organs:** **Q**, vulva (details); **R**, membranous folding plate of the vulva; **S**, washboard; **T**, surface of stridulatory ribs.

**Gnathochilarium:** The ventral side has several bristles and a very few bristles on lingual lamella. Central pads with a few isolated sensory cones and bristles are found on stipites.

**Tergites:** Anterior end of the tergites consist of small granules and half of the tergites are densely punctured and hairy. The posterior margin with a few puncture and the posterior half is smooth and shiny. Marginal bristles are not extending over the border. The 8<sup>th</sup> tergite width is 5–6 mm, height is 12–13 mm and length is 19–20 mm.

**Endotergum:** It consists of two rows of marginal bristles and they are thin, long and cover half of the length. The central area has randomly distributed fine bristles and small spines.

**Anal shield:** It is slightly bell-shaped and densely punctured. The two black locking carinae on either side and the anterior one is double the length of the posterior one. Posterior carinae are closer to the margin compared to the anterior one. A conspicuous suture is present between the carinae and a small invagination is found in the region where the suture meets the margin. At the ventral side of anal tergite, 3–4 annular rings are present and it is covered by fine short hairs. The dorsal side is punctured with a few isolated fine hairs. Numerous sclerotised spots are found on the ventral side, which has random distribution. A single row of conspicuous sclerotised spots is found on the inner portion of the pygidium.

**Legs:** Tarsi is 1–3 with an apical spine and 4 ventral spines. Apical spine is thick and stout. Tarsi 4–8 with 8 ventral spines and weekly curved claw and rest of the tarsi has 9 ventral spines. Femurs of most of the legs have darkly crenulated spots. Legs are covered by short fine hairs and 9<sup>th</sup> leg with coxal lobe.

**Stigmatic plates:** Lobe is flat and apex almost triangular covered with short hairs. Apical portion of the plate is hooking towards femur with a few isolated sclerotised spots.

#### 4.1.1. Male sexual characters

**Gonopore:** Second pair of leg with male gonopore is one-fourth in size of coxa and covered by single divided, oval-shaped sclerotised plate. Large and small plates are divided by membranous structure. A few short fine hairs found on entire region of coxae of second pair of legs at apical region possess isolated long hairs.

**Anterior telopods:** Pre-femur of anterior telopods has sharp edges. First podomere possesses strongly pronounced two stridulatory ribs (one is longer and another is shorter). Second joint is slightly hooking towards the third podomere. A few sclerotised spots are found on apical portion of third podomere. Final podomere has two blunt lobes covered with long hairs. Right and left segments of anterior telopods hook each other and attain slightly horse shoe-shape.

**Posterior telopods:** Syncoxite has tuft of long bristles. Elongated movable finger weakly curved towards fixed finger. Movable finger has two lappets, mesal one is thicker and larger than apical one. About 16–18 crenulated teeth present on movable finger as well as numerous sclerotised spots exist on fixed finger. Movable finger is thick at the base and gradually tapers towards the apex with slightly blunt tip. Movable finger is slightly hooking towards the fixed finger. Both the horns are facing outwards with thick pointed apical regions covered by fine hairs. Fixed finger has a few isolated hairs but movable finger is almost glabrous. A few isolated sclerotised spots are found on the apical region of inner horns.

#### 4.1.2. Female sexual characters

**Vulva:** The second pair of legs possess coxal lobe. The well-developed vulva is and larger covers three-fourths the coxal length. Mesoapical portions are covered by thick hairs. The operculum is long, which is slightly disc-shaped and has shallowly intended in the middle. Medium size mesal plate is fairly thin extending beyond coxa and operculum. The apical portion is covered with short hairs. The left mesal plate is slightly longer and both are hooking towards pre-femur. The operculum is fairly covered by hairs. The outer plate is slightly round and has thickened region in the middle. Sub-anal plate with washboard bears 3 stridulation ribs on each side and margins consist of short hairs (2 are long, well developed and the remaining one is short).

#### 4.1.3. Distribution and ecology

**Distribution:** Currently, these millipedes were recovered from mixed plantations of Adyanadka, foothills regions of Western Ghats of India. This plantation is rich in *Areca*, *Cocoa*, banana and coconut plants. The plantation has been strictly organically managed with adequate irrigation during the dry season and animals are active most of the year.

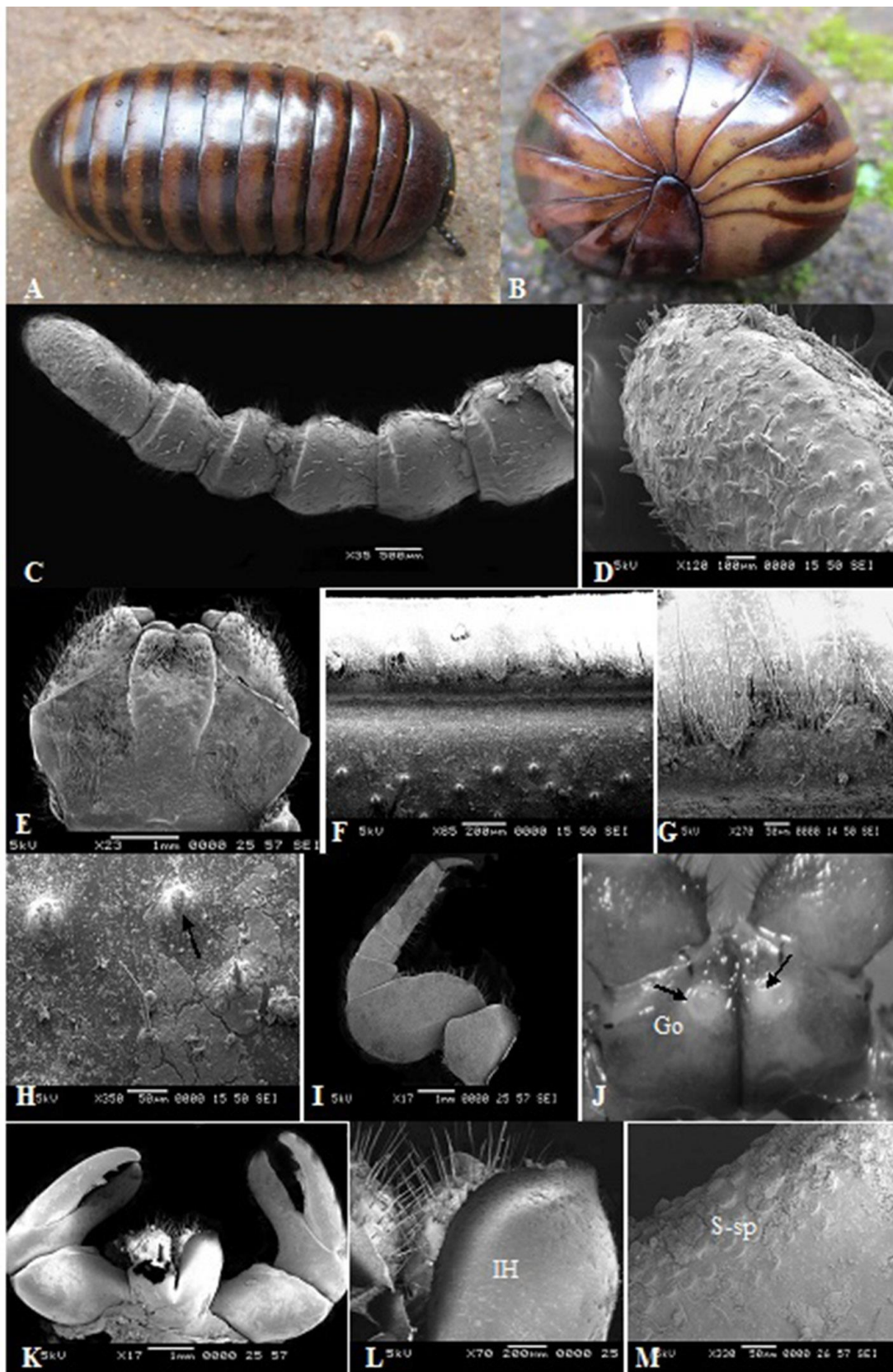
**Life history and intraspecific variation:** Male is slightly bigger than female (n=16). Juveniles have well-developed sexual organs and are more active than adults. Female consists of up to 700–800 eggs during the reproductive season. The animal usually moves for hibernation in late summer. No color variations are seen between males and females.

**Conservation:** Present condition of mixed plantations is directly linked to the conservation of this species. Unfortunately, human interference is increasing and the fate of this animal is decided by future human activities. The use of artificial fertilizer and pesticides in the future may lead reduction in animal density or leading to extinction.

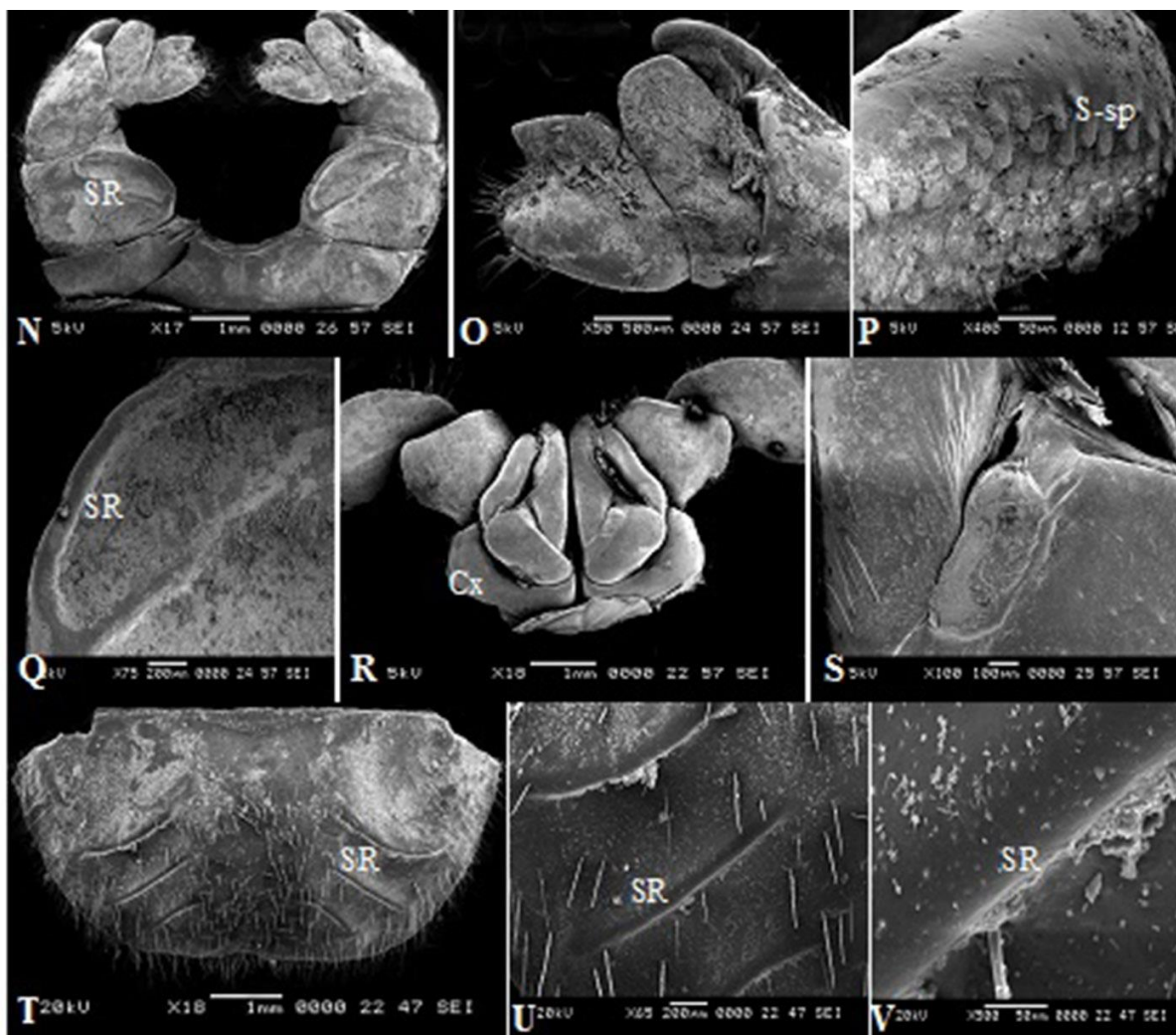
#### 4.2. *Arthrosphaera dalyi* Pocock 1899 (Figure 2a and 2b)

**Locality:** This millipede has been collected from the forest floors and from mixed plantations of Ninthikal of the Western Ghats, Southern India (12°39' N, 75°26' E). Depth of litter was 2–5 cm and litter temperature 27–28°C. The specimens are preserved in the zoological museum of Mangalore University, Karnataka, India (MUAZPMAdI-02).

**Diagnosis:** Length is up to 46 mm and weighs up to 13 g. The colour is deep-brown and the posterior border are reddish. Head, collum and thoracic shields are specious. The antennae and legs are green. Basal segments of legs are ochraceous. The anterior half of the tergites are densely pubescent. The second tergite margin thickening is small. Tergite margin is with a small notch. The inner crest is single and rather longer than that of the preceding tergite. The female washboard has three stridulation ribs. Male is comparatively bigger than female.



**Figure 2a.** *Arthrosphaera dalyi* Pocock. **A**, moving animal; **B**, conglobated animal; **C**, right antenna; **D**, last antennomere with sensory cones; **E**, gnathochilarium ventral side; **F**, endotergum overview; **G**, posterior margin; **H**, the internal area of endotergum (arrow, spine); **I**, the leg portion of the vulva. **Male sexual organs:** **J**, holotype of the second coxa with male gonopore (arrows); **K**, posterior telopods; **L**, inner horns of posterior telopod; **M**, sclerotised spots on chela.



**Figure 2b.** *Arthrosphaera dalyi* Pocock. **N**, anterior telopods (anterior view); **O**, final podomere; **P**, sclerotised spots on podomere of anterior telopod; **Q**, ribs on telopods (overview). **Female sexual organs:** **R**, vulva (details); **S**, membranous folding of the vulva; **T**, washboard; **U**, stridulatory ribs of washboard; **V**, Surface of stridulatory ribs.

**Body length:** Holotype: Male length is up to 46 mm and in females it is up to 45.5 mm (n=20). Weight varies from 6.3–12.9 g. Breadth is ranges from 14.1–24.3 mm. Male widest axis ranges from 19.3–35.6 mm and in female 26.3–35.1 mm. Narrow axis of male varies from 15.6–26.7 mm and in female ranges from 14.9.5–25.9 mm.

**Habitus:** Large size animal, tergite's margin has a small notch and round pygidium.

**Coloration:** Deep olive-brown, posterior border of the tergite is reddish. The antennae and legs are green. The head and nuchal plate are dark-brown.

**Head:** Smooth and polished with setiferous pits around the central pad as well as the lateral side of the eye. Eyes consist of ~85–93 ocelli. Sparse long hairs are found at the posterior margin. Mandible has a small furrow near the apical portion. About 5 pectinate lamellae possess long and thin teeth and the number of teeth decrease proximally. The mouthparts are not dissected.

**Collum:** Polished, smooth with a few isolated long hairs and the posterior margin has a tuft of hairs at the center.

**Thoracic shield:** Colour mimics the tergites and a few hairs are present on the lateral extension. The marginal brim has slightly broader in the anterior region.

**Antennae:** The antenna consists of six green-colored antennomeres. The terminal disc is narrow and oval-shaped. The first antennomere is broader compared to the remaining ones. Length of antennomere: 1>2=3>4=5<6. The sixth antennomere is the



longest and the terminal disc has more than 78 sensory cones. Hairs are present in between sensory cones. The entire surface of the antennae is covered by fine hairs.

**Gnathochilarium:** Many hairs are randomly distributed on the posterior surface. A few hairs are present on lingual lamella and a few sensory cones exist on palpus.

**Tergites:** Surface smooth, polished, pubescent and densely punctured in the front part. Tips of the para-tergite project posteriorly. Marginal bristles are not extending over the border. Para-tergite depression of anterior region has several ridges but they are absent on the posterior side. The length of the 8<sup>th</sup> tergite is 20–21 mm; width 6–7 mm; height 11–12 mm.

**Endotergum:** There are two rows of marginal bristles and they are thin, long and cover half of the length. The inner area has fine bristles and small spines are randomly distributed.

**Anal shield:** Round anal shield is densely punctured and pubescent throughout. The ventral side carries 2 black locking carinae on either side. The posterior carinae are closer to the margin compared to the anterior one. A distinct suture exists between the carinae and small invagination is seen at the end of the margin. Five annular rings exist at the ventral side of anal tergite and they are covered by a carpet of fine short hairs.

**Legs:** Tarsi of 1–2 with apical spine and 2–3 ventral spines mostly covered by fine hairs. Remaining tarsi consist of 9–11 ventral spines with curved claws. The ninth leg is devoid of the coxal lobe. Coxae of all the legs at the inner margin are covered by long hairs.

**Stigmatic plate:** Lobe is almost triangular and covered by short hairs. The apical portion of the plate is hooked towards pre-femur.

#### 4.2.1. Male sexual characters

**Gonopore:** Gonopore is covered by a single undivided, round sclerotised plate, which covers nearly one-fourth of the coxa. A few short fine hairs are present on the entire region of coxae of the second pair of legs.

**Anterior telopods:** Harp with two stridulation ribs. A femoral process situated behind the tibio-tarsus is blunt. The tibia is separated by a lobe. The tarsal process has three lateral blunt cones. Margins of the first podomere possess hairs, while the surface with sparse hairs. The third podomere is slightly cupped towards the second one. The final podomere consists of ~30–35 sclerotised spots and ribs at the posteroapical region.

**Posterior telopods:** Syncoxite possesses a few hairs. Elongated movable finger weakly curved towards the fixed finger. Coxal horns are dark-brown and has pointed tip. The movable finger has two white lappets, mesal one is thicker than the apical one. The tips are hook-shaped. The length of the fixed finger is equal movable finger and facing toward each other. Many sclerotised spots are found on the mesoapical region of the fixed finger. The opposite finger has crenulations juxtaposed to a crenulated tooth of the movable finger (~16–17). A tuft of hairs on the apical portion of the inner horn and facing outwards. A few isolated sclerotised spots are seen on the apical region of the inner horns.

#### 4.2.2. Female sexual characters

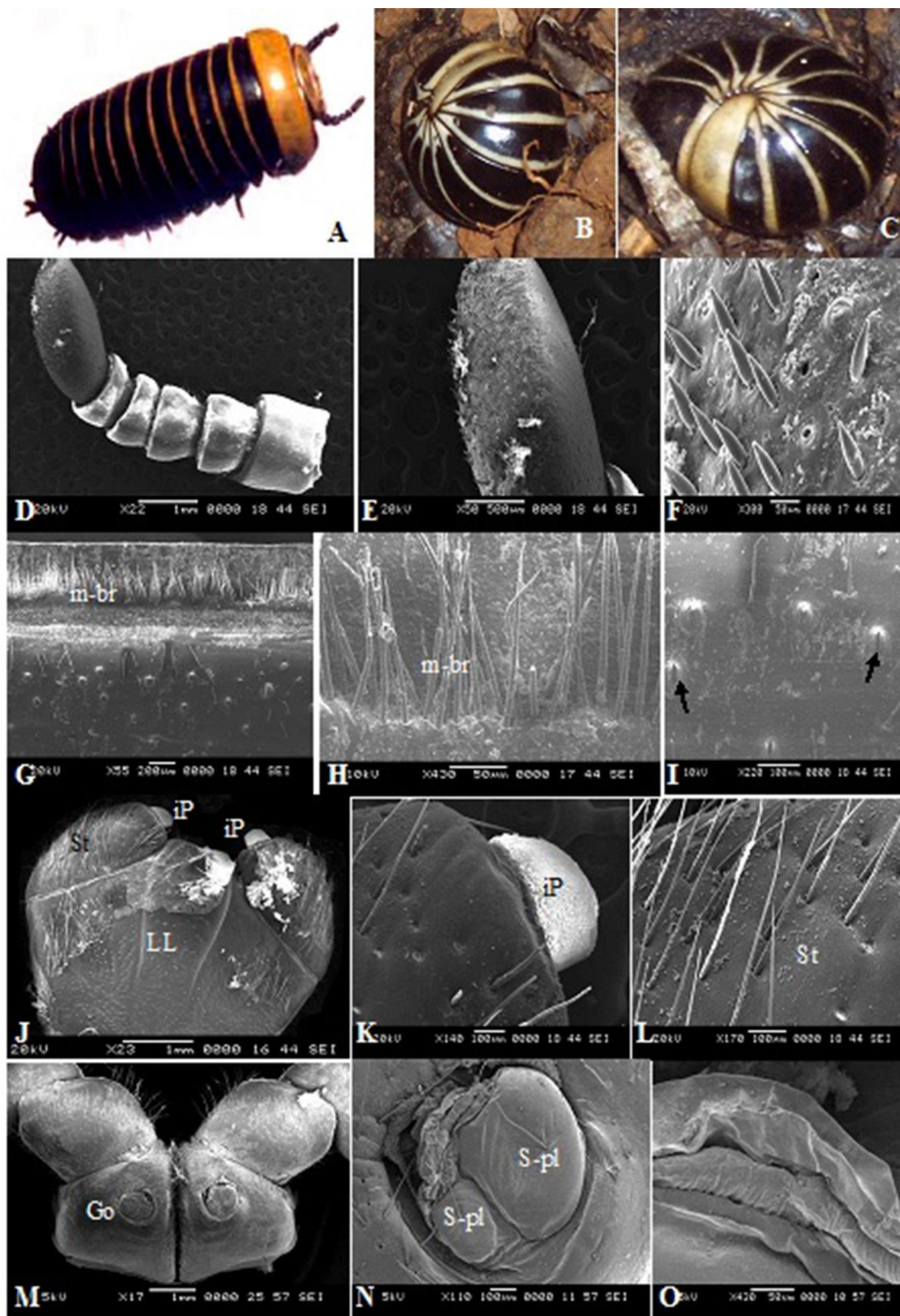
**Vulva:** The second pair of legs has no coxal lobe. The large vulva covers three-fourths of the length of the coxa. The operculum is long and thin. The mesal plate is slightly long and broad, extending fairly beyond the coxa as well as operculum. The apical portion is covered with short fine hairs. The anterior margin is devoid of any indentation and lower margin has an indentation at the center. The exterior plate is smaller than the inner plate. The anterior margin of the inner plate is below the base of the operculum. The operculum has a few isolated sclerotised spots and is fairly covered by hairs. Sub-anal plate with washboard bears three stridulation ribs on each side. The third rib is long, thin and well developed.

#### 4.2.3. Distribution and ecology

**Distribution:** Animals are abundant in the Nynthikal and Panja region of the Western Ghat foothills. Animal is mainly inhabited in the mixed plantation as well nearby forest region. The density of animals is more in the plantations compared to forests. Organic farming as well as traditional agricultural practices attracted more animals from forest regions to the plantations. During the entire year, moist condition prevails in plantations compared to the dry forest area. Even during summer animals are active because of continuous irrigation practice. Juveniles are active till January and later they migrate for hibernation close to the moist areas.

**Intraspecies variation:** Body length, and size of males and females are almost equal. Juveniles are light brown compared to dark adults. Most of the recovered juveniles showed well-developed reproductive systems.

**Conservation:** Several patches of plantations and adjacent forests support the propagation of this millipede. Conservation of these millipedes mainly depends on the cultivation of mixed plantations along with wild plant species and the practice of organic farming.

4.3. *Arthrosphaera davisoni* Pocock 1899 (Figure 3a and 3b)

**Figure 3a.** *Arthrosphaera davisoni* Pocock. **A**, moving animal; **B–C**, conglobated animal; **D**, left antenna; **E**, shoe-shaped last antennomere; **F**, sensory cones on distal antennomere; **G**, endotergum overview; **H**, posterior margin, **I**, the internal area of endotergum (arrows, spines); **J**, gnathochilarium ventral side; **K**, palpus; **L**, bristles on stipites. **Male sexual organs**: **M**, holotype, second coxa with male gonopore; **N**, right gonopore; **O**, membranous folding of gonopore (anterior view).

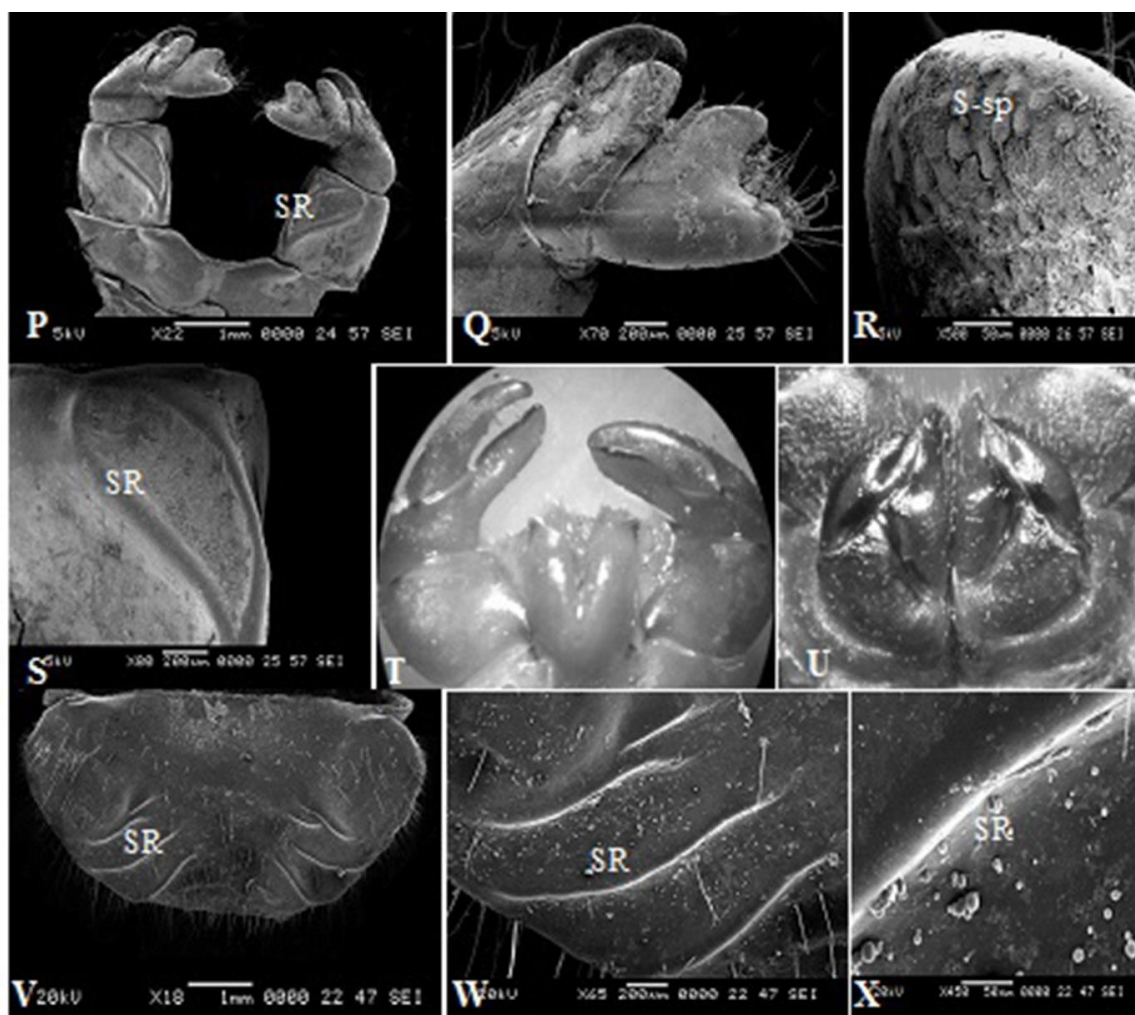
**Locality:** This millipede has been located in high altitude ranges of Kudremukh, Western Ghats of Southern India (13°12'N, 75°16'E). Common in cardamom mixed plantation and also from adjacent forests. The specimens are preserved in the museum of Mangalore University, Karnataka, India (MUAZPMAda-03).

**Diagnosis:** Up to 49 mm long, 25 mm wide and weigh about 14 g. Male is slightly bigger than female. The colour is brownish-black with variegated irregular spots and a yellow band at the posterior margin. Antennae are olivaceous with more than 93 sensory cones at the apical disk. Anal tergite is somewhat saddle-shaped and densely punctured. A pit-like depression was seen on the anterior inferior angle of the pygidium. The female washboard has 4 ribs on each side. Two well-grown black locking carinae are present on either side of the anal tergite and the anterior one is 3 times longer than the posterior one.

**Body length:** Male length up to 49 mm and width up to 25 mm (n=5). Female length up to 46 mm and width up to 23 mm (n=2). Females are comparatively smaller than males.

**Habitus:** Medium size with the golden-brown legged animal. Tergites are densely punctured and rectangular holotype bodies.

**Coloration:** Black individuals possess a posterior yellow border. The head olivaceous and posterior portions of tergite is slightly darker than the anterior. Collum and thoracic shields are yellowish and antennae are olivaceous with yellow sensory areas. Legs are brown and tarsi are olivaceous.



**Figure 3b.** *Arthrosphaera davisoni* Pocock. P, anterior telopods (anterior view); Q, final podomere; R, sclerotised spots on podomere of anterior telopod; S, ribs on telopod (surface); T, posterior telopods. Female sexual organs: U, vulva (details); V, washboard; W, stridulatory ribs of washboard; X, the surface of stridulatory ribs.

**Head:** Head is densely punctured with many hairs. Eyes possess 89–93 ocelli, mandible with 31–34 fine teeth, which are arranged in rows. Mouthparts, are not dissected. Posterior margins are devoid of fine hairs. Hairs are found around the central clypeus and lateral side of the eye. Collum is yellow with fine short hairs on anterior margins and the rest of the collum is hairless.

**Gnathochilarium:** Ventral side of gnathochilarium has many hairs and very few hairs on lingual lamella. Palpi have a few sensory cones. The central pad has very minute hairs. Lingual lamella has 16–19 pits with hairs.

**Antennae:** Antennae consist of six antennomeres and the apical disc is laterally expanded. It consists of more than 93 sensory cones. Sensory cones are blunt at the apex. Length of antennomeres in the order: 1>2=3>4=5<6. The first antennomere is slightly broader and bigger in size compared to other antennomere.

**Thoracic shield:** Colour mimics the tergite and the anterior rim is slightly broader than the rest of the terga. Lamina is small and abruptly thickened opposite to their eyes.

**Tergites:** Tergites are densely punctured in the upper region. The posterior tergites are pubescent in the front portion. Para-tergites consist of a few isolated hairs and ridges. The posterior projection of para-tergite tip is conspicuous. The posterior half of the terga is not polished. Length of the 8<sup>th</sup> tergite is 18–20 mm; height is 15–18 mm and width is 11–13 mm.

**Endotergum:** The endotergum possesses a double row of the marginal bristles to attain up to half of the distance from the edge of the margin. The internal area consists of thick short spines as well as very few long bristles. There are no inner cuticular impressions.

**Anal shield:** Slightly saddle-shaped and densely punctured and the surface possesses a few isolated short hairs. Margin has single pit-like depression. The ventral side consists of 2 black locking carinae on either side. Anterior carinae measure thrice the length of the posterior carinae. Distinct sutures exist between the carinae and weak invagination is found at the region where the suture meets the margin. Four annular rings were found on the ventral side which was finely covered by very fine short hairs. A few sclerotised spots are randomly distributed on the ventral side of the pygidium.

**Legs:** Golden-brown legs possess olivaceous tarsus. Tarsi 1–2 consist of 2 ventral spines; 3–9 have 13 ventral spines; 10–21 possess 11 ventral spines. The first two pairs of legs with apical spines and the remaining pairs possess weakly curved claws. Tibia is covered with fine hairs.

**Stigmatic plates:** Plate has a broad base narrow apex lobe with fine hairs. Lobe is short and the apex curved towards pre-femur.

#### 4.3.1. Male sexual characters

**Gonopore:** Gonopore is present on the second pair of legs and covered with two plates one is smaller another one covers three-fourths of the area. The entire gonopore covers half the height and half the width of the coxa. Fine hairs are present in the apical region.

**Anterior telopods:** The pre-femur of anterior telopods possesses a sharp edge behind. The harp possesses 2 stridulatory ridges. Femoral processes are found behind the tibio-tarsus and not visible from front, which is short, blunt and curved. Tibia and tarsus clearly separated. Tibia has a round lobe at the apex. Tarsus above and behind possesses a rounded lobe with a blunt cone near the apex. The final podomere has ribs and sclerotised spots. Hairs are sparse hairs on the surface of telopods.

**Posterior telopods:** Coxal horns of the syncoxite with a dark lateral claw at the apex. The femoral process is thick, pointed and lengthier than the tibia. Tibia with 2 separated white lappets and margins roofed with well-grown knobs. Movable fingers have ~14–16 crenulated teeth and numerous sclerotised spots on the fixed fingers.

#### 4.3.2. Female sexual characters

**Vulva:** Coxae in the second pair of leg possess vulva and covers almost the whole coxal part. The proximal region of the vulva is smaller compared with the distal portion. The operculum is long as well as devoid of any central invagination. The basal portion has a black indentation. Long as well as broad inner plates surpass the operculum. The inner plate is longer than the exterior plate. Apical regions are covered by fine hairs. Sub-anal plate with washboard possesses four stridulation ribs on each side.

#### 4.3.3. Distribution and ecology

**Distribution:** This species was collected from the plantations of the Kudremukh region, Karnataka. Slopes of plantations support the normal propagation of this millipede. Mainly cultivated crops like areca, cardamom, pepper and coffee are the plantations in this region. The abundance of millipedes is more in plantations than in nearby forest regions.

**Intraspecies variation:** Male is slightly bigger than female and there is variation in the length of the antenna between male and female.

**Conservation:** Species-specific dominance is common in *Arthrospiraera* including *A. davisoni*. The future of this millipede is dependent on the condition forest as well human pressure. No conservation efforts are made and ongoing anthropogenic activity may threaten this species in the Kudremukh region.

#### 4.4. *Arthrospiraera disticta* Pocock 1899 (Figure 4a and 4b)

**Locality:** Found on the forest floor of Shimoga, Western Ghats of Southern India (13°43'N, 75°37'E). Collected from the wet leaf litter on the forest floor with litter depth 4–5 cm and temperature 26–27°C. The specimens were preserved in the zoological museum of Mangalore University, Karnataka, India (MUAZPMAdi-04).

**Diagnosis:** Up to 27 mm long, 12 mm wide and weighs about 1.7 g. Female is bigger than male. Colour olive-yellow, deep-red, brownish-black with variegated spots or without spots and tergites have a posterior deep green margin. Tergites except for anal tergite possess black patches in the anterior region. The thoracic shield is three-fourths covered by deep green patches and thickened in the region opposite the eye, which is olive-green in color. Antennae are in dark green with more than 110 sensory cones at the apical disk. Anal tergite is ovently convex and not sulcate. Anterior telopods have ridges on the second segment and long membranous projection present on the basal region of the movable finger (posterior telopods). Two well-grown black locking carinae are present on either side of the anal tergite as well as anterior one is double than the length of the posterior one.

**Body length:** Males are up to 24 mm in length and width up to 10 mm (n=30). Females are up to 27 mm in length and width up to 12 mm (n=30).

**Habitus:** The second tergite with small lamina and thoracic shield is smooth. Tergites are densely and finely punctured and covered with fine pubescence.

**Coloration:** Colour is deep olive-yellow with variegated black spots or deep-red without spots or blackish or greenish-brown with brown spots. Tergites are deep green borders at the posterior margin. The head, antennae and legs are deep-green. The thoracic shield has a large deep green patch, which covers three-fourths of the area. The anterior half of the tergites are with irregular black patches which are almost absent on the anal tergite.

**Head:** Head is densely punctured, eyes with ~74–82 ocelli and mandible with ~34–36 fine teeth arranged in rows. Mouthparts are not dissected. Collum is dark green or brown with dark green patches almost three-fourths of the collum, fine short hairs on the edges and the rest of the collum are glabrous. Gnathochilarium ventral side covered by many bristles and a thick tuft of bristles present on lingual lamella with a few sensory cones on palpus. Central pads possess very minute hairs.

**Antennae:** Antennae consist of six antennomeres and are covered by fine hairs. The apical antennomere is shoe-shaped and poses more than 110 sensory cones. Sensory cones are blunt at the apex. Length of antonomeres: 1>2=3>4=5<6. The first antennomere is broader and bigger in size compared to other antonomeres. Antonomeres are devoid of sclerotised spots.

**Thoracic shield:** It is smooth and margins opposite to eyes are slightly thickened, crossed above by an arched groove, densely punctuate and pubescent.

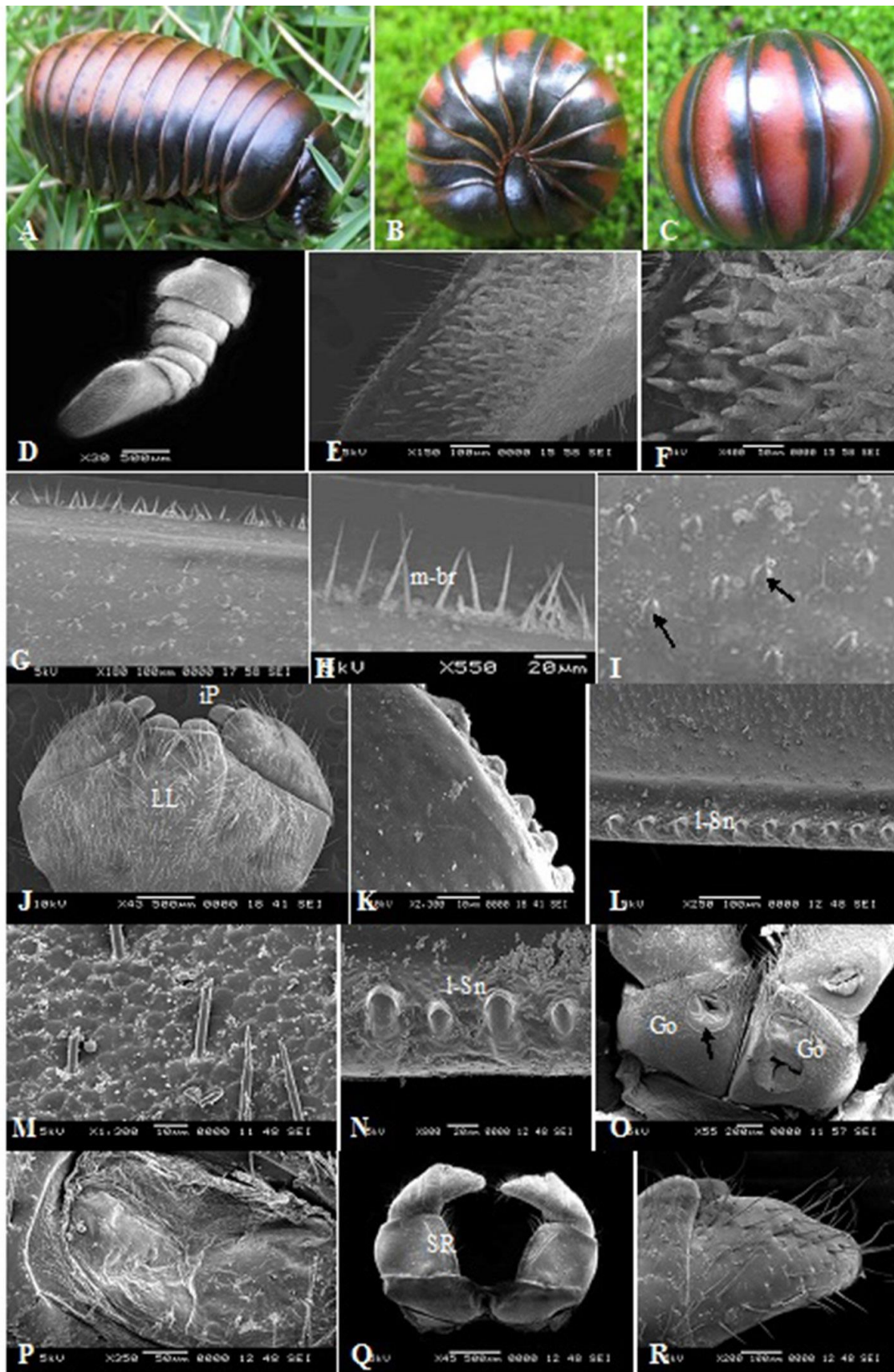
**Tergites:** Surface smooth, second tergite with small lamina, with black dots, the crest of the tergites finely punctured and covered with fine pubescent. Alcohol seems to quickly runoff from the specimen. The eighth tergite is with 11–12 mm height, 5–7 mm width and 3–5 mm breadth. The external sub-marginal area of the anterior region consists of a row of round sclerotized nodules. A central area is dominated by short nodules and setae. Posterior margins possess short setae.

**Endotergum:** A double row of marginal bristles reaches three-fourths of the distance to the edge of the margin. The internal portion has thick short spines with very few isolated long scaly bristles. No inner cuticular impressions.

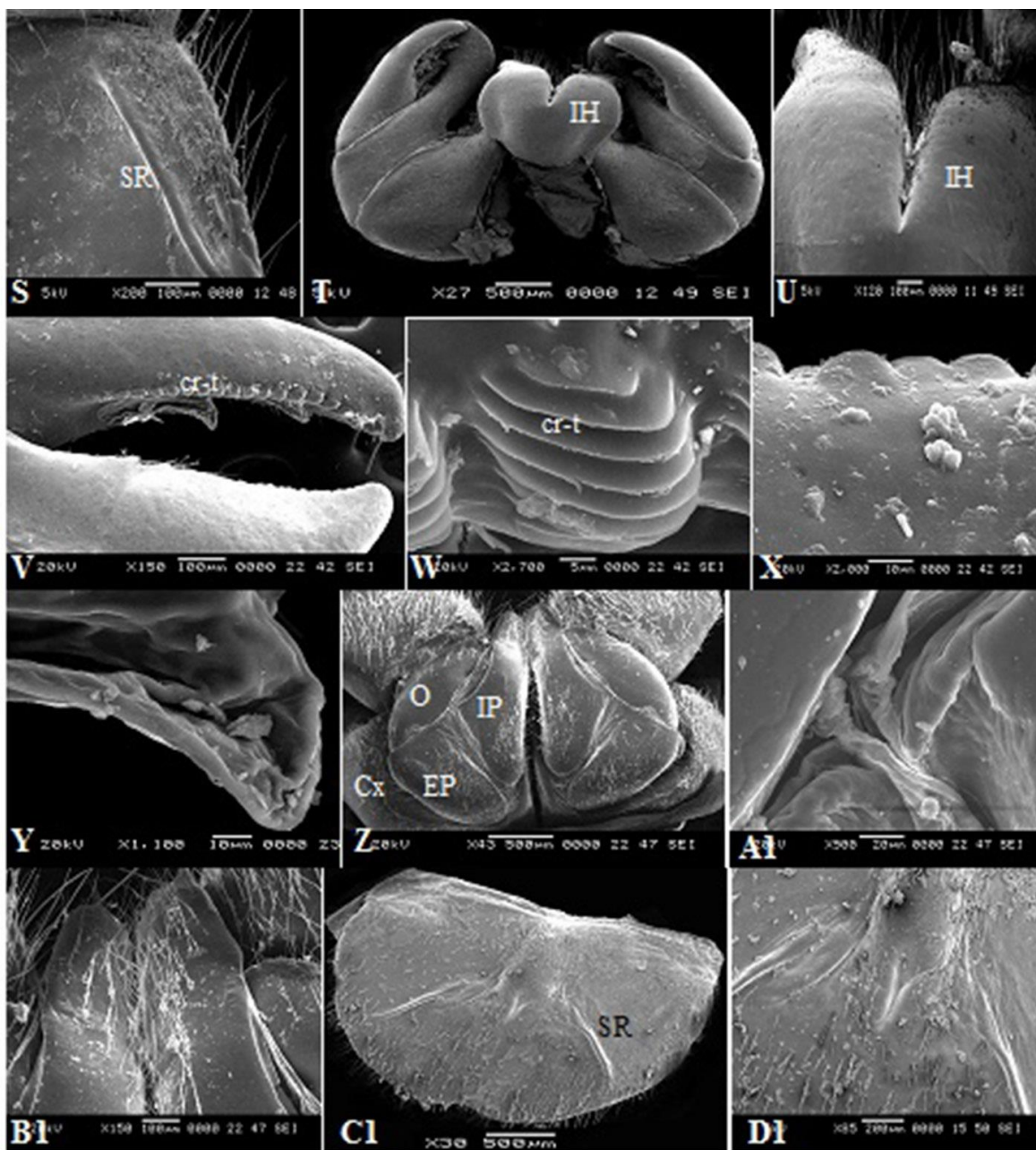
**Anal shield:** Ovently convex, devoid of black patches, surface with a few isolated short hairs. The ventral side of pygidium consists of 2 black locking carinae on each side. The length of the anterior carinae is double than the posterior carinae. Margins are not sulcate. The distinct suture is present between the carinae representing the border of the 13<sup>th</sup> segment fused with anal tergite. A very weak invagination is visible at the region where the suture reaches the margin. Eight annular rings were found on the ventral side, which are finely covered by very fine short hairs. The 4<sup>th</sup> and 6<sup>th</sup> annular rigs show a typical branching pattern.

**Legs:** Legs dark-greenish, tarsi 1–2 possess 2 ventral spines; 3–9 with 12 ventral spines; 10–21 with 10 ventral spines. The first two pairs of legs possess apical spines and the remaining pairs have a weakly is curved claw. Tibia covered with fine hairs.

**Stigmatic plates:** The plate possesses a broad base narrow blunt apex lobe with fine hairs. The lobe is short as well as the apex curved towards coxa.



**Figure 4a.** *Arthrosphaera disticta* Pocock. **A**, moving animal; **B-C**, conglobated animal; **D**, right antenna; **E**, shoe-shaped last antennomere; **F**, sensory cones on distal antennomere; **G**, endotergum overview; **H**, posterior margin; **I**, the internal area of endotergum (arrows, spines); **J**, gnathochilarium ventral side; **K**, palpus with sensory cones; **L**, tergite; **M-N**, central area and nodule of the anterior region of tergite. **Male sexual organs**: **O**, holotype of the second coxa with male gonopore (arrow, gonopore); **P**, the surface of gonopore; **Q**, anterior telopods (anterior view); **R**, apical portion anterior telopod.



**Figure 4b.** *Arthrospuera disticta* Pocock. S, the surface of stridulatory ribs; T, posterior telopods (anterior view); U, inner horns; V, right chela, posterior view; W-X, crenulated teeth and sclerotised spots on right chela; Y, membranous lobe of right chela. **Female sexual organs:** Z, vulva (details); A1-B1, membranous folding and apex of inner plate of the vulva; C1, washboard; D1, stridulatory ribs of washboard with suture.

#### 4.4.1. Male sexual characters

**Gonopore:** Gonopore is present on 2<sup>nd</sup> pair of legs. It is covered with a single, undivided, spherical sclerotised plate with a membranous fold inside. Cover one-fourth of the height and half of the width of the coxa. A tuft of hair shields the apical part of gonopore.

**Anterior telopods:** The first podomere has a single stridulatory rib. The surface of the stridulatory ribs is plain with a few sparse hairs. The lateral edge of syncoxite close to the first podomere also possesses very few isolated sclerotised spots. The second podomere process pointing towards the third podomere covers the entire length of latter one. Third podomere bears numerous sclerotised spots at the apex. The final podomere possesses two lobes with sclerotised spots and crenulated teeth covered by short hairs. The anterior telopods curved to each other and attain almost a horseshoe shape.

**Posterior telopods:** Movable fingers are thick at the base and partially curved at the tip. The movable fingers possess ~17 crenulated teeth as well as two membranous lobes. The 1<sup>st</sup> lobe is larger and thicker compared to the second one. The fixed finger is shorter compared to the movable finger and possesses numerous sclerotised spots. A few isolated hairs are present on both the fingers. The first podomere possesses sparse hairs on the surface. The tip of the inner horns are black as well as curved outwards. The inner lobe is quite flat and pointing inward attaining almost a bowl shape.

#### 4.4.2. Female sexual characters

**Vulva:** Coxae of 2<sup>nd</sup> pair of leg possess vulva and it is large, occupies most of the coxal region. The operculum is short and deeply sulcate at mesoapical portion. The mesal plate is long, wide at the base, narrow towards the apex and extends beyond the coxa as well as operculum. It is covered with dense hairs at the tip region. Left mesal plate hook towards pre-femur (in some cases straight) and the right one is almost straight. The right mesal plate possesses small invagination in the mesal region. The SEM analysis shows that the sub-anal plate with the washboard possesses a single stridulation rib on each half. Middle of the washboard possesses a clear suture, which reaches half of the length and is covered with sparse hairs.

**Life history:** Adult *A. disticta* were collected during the post-monsoon season in 2012. Nearly 200–400 eggs were found in most of the sacrificed adult females and they are aggregated into many clusters between the body wall and intestine, like a conveyor belt from the second pair of legs to the pygidium. Eggs are round and light-yellow to ivory-colored. The diameter of eggs varies from 1.5–2 mm and eggs are preserved in 70% ethanol.

#### 4.4.3. Distribution and ecology

**Distribution:** This is the smallest known individual in the genus *Arthrosphaera*. This species was collected from the semi-evergreen forest region of Shimoga, which has more human interference but the density of animals is too high in this region. This region of the Western Ghats receives good rainfall and this consists of *Terminalia* sp. likely provide sufficient litter strata for the growth and propagation. The habitat has a slope with thick vegetation and drains water easily. They showed the behavior of climbing the building walls, probably due to their small size as well as lightweight and such climbing activities to the canopy of trees need to examine.

**Intraspecific variation:** Male is smaller than female but some weigh almost the same. Most of the recovered juveniles showed well-developed telopods as well as washboards. Colour variations are there between males, females, and males and females. A few individuals possess black spots, but very few without any variegated spots. Colour varies from olive-yellow, deep red and blackish-brown with a greenish tint and greenish-brown shade.

**Conservation:** The *Terminalia* forest of Shimoga seems to be an ideal habitat for *A. disticta* and deserves stringent conservation measures. Unfortunately, human interference is increasing in the heart of the forest especially fragmentation by roads, subways and electrical cables. As the population of *A. disticta* is very high in this region, roadkill is very common due to vehicular traffic. At present no conservation measures are imposed to restrict human activities.

#### 4.5. *Arthrosphaera fumosa* Pocock 1899 (Figure 5a and 5b)

**Locality:** It is abundant in the Karike region of Western Ghats (12°27'N, 75°23'E). Collected from the forest floors as well as mixed plantations. Leaf litter depth was 4–6 cm with a temperature of 27–28°C. The specimens are preserved in the zoological museum of Mangalore University, Karnataka, India (MUAZPMAf-05).

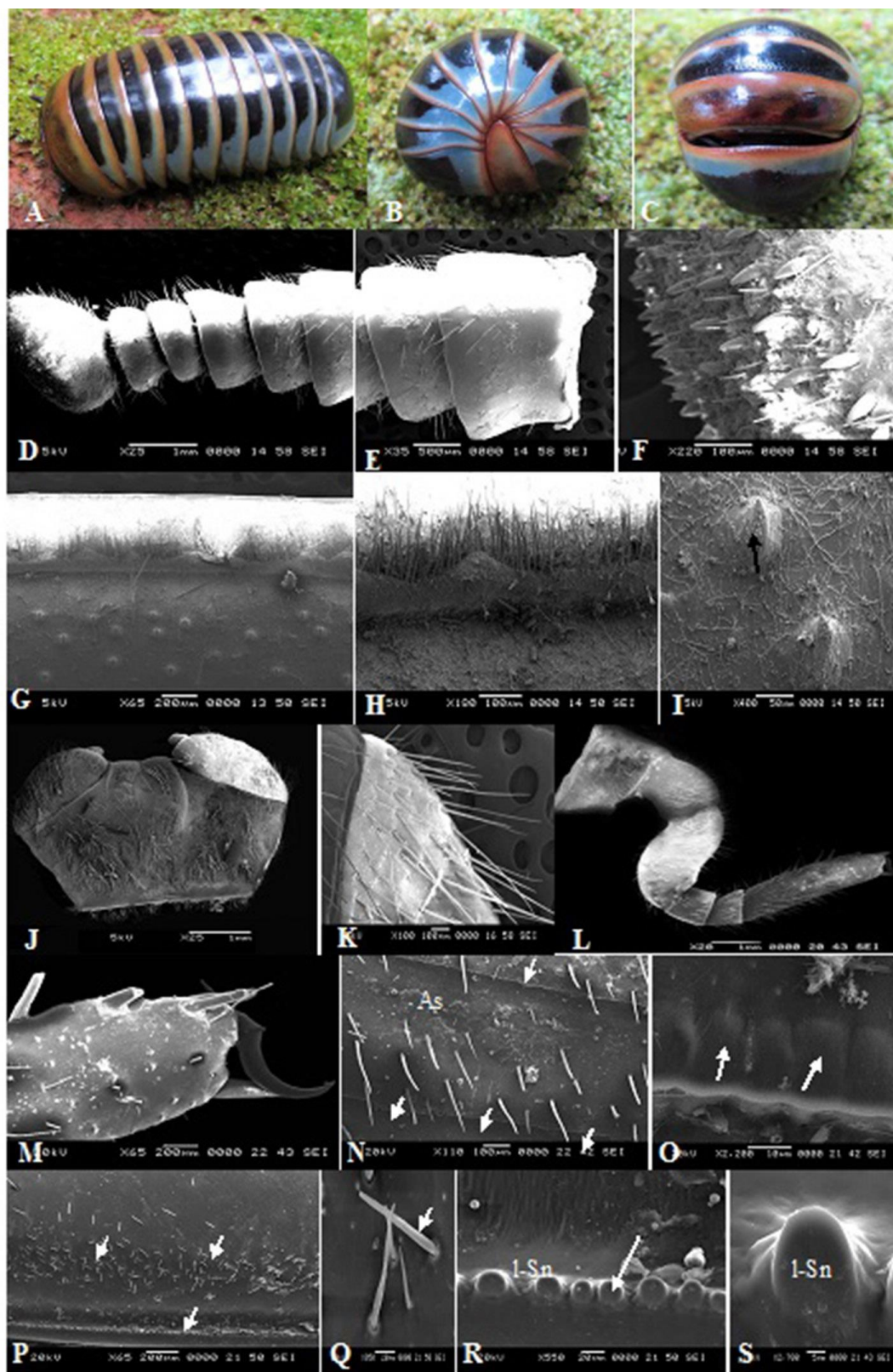
**Diagnosis:** Up to 48.5 mm long, 23 mm wide and weighs about 16 g. Female is slightly bigger than male. The colour is pale-olivaceous, the posterior half of the tergite except the thoracic shield and anal shield is smoky black, and the legs and antennae are deep olive green. Collum possesses pale blotches and short hairs. The apical disc of antennae consists of ~94–98 sensory cones. Two well-grown black locking carinae exist on both sides of the anal tergite and the anterior carinae is double the length of the posterior carinae.

**Body length:** Males measures up to 46 mm long and up to 23 mm in width (n=50). Females possess lengths up to 48 mm and widths up to 23 mm (n=50). Male is comparatively smaller than female.

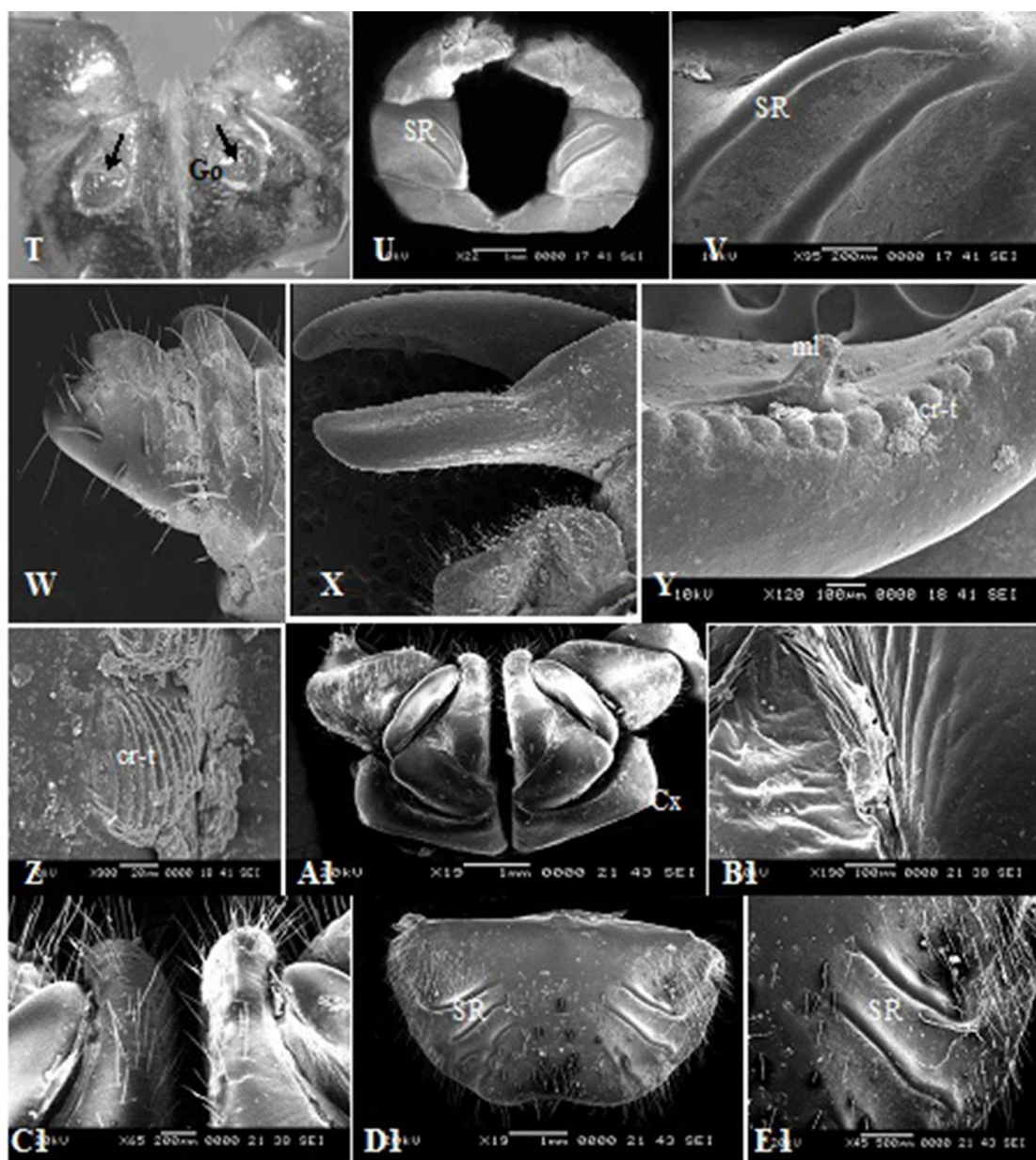
**Habitus:** Head and collum thoracic shield are pectious and basal segments of legs are pale in color. Tergites are rugose, finely punctured and covered with fine pubescence.

**Coloration:** Pale-olivaceous or ivory or sky-blue or pale-green with variegated smoky black spots on the posterior half except for the second and anal tergites. Collum has pale blotches and a few isolated black spots. The antennae and legs are deep olive green.





**Figure 5a.** *Arthrosphaera fumosa* Pocock. **A**, moving animal; **B**, conglobated animal; **C**, conglobated animal with thoracic shield; **D**, right antenna; **E**, first antennomere; **F**, last antennomere with sensory cones; **G**, endotergum overview; **H**, posterior margin; **I**, internal area of endotergum (arrow, spine); **J**, gnathochilarium ventral side; **K**, palpus with a tuft of bristles; **L**, leg; **M**, curved claw of leg; **N**, pygidium with annular rings, **O**, cuticular impressions (arrows), **P**, ventro region of tergites (arrows, setae); **Q-S**, setae, row of nodules and nodule.



**Figure 5b.** *Arthrosphaera fumosa* Pocock. **Male sexual organs:** T, holotype, second coxa with male gonopore (arrows, gonopore); U, anterior telopods (anterior view); V, ribs on anterior telopod; W, apical portion of anterior telopod; X, posterior telopod right chela (anterior view), Y, row of crenulated teeth on the fixed finger; Z, crenulated teeth. **Female sexual organs:** A1, vulva (details); B1-C1, membranous folding and apex of inner plate of the vulva; D1, washboard; E1, stridulatory ribs of washboard.

**Head:** Polished and coarsely punctured below. Numerous hair and setiferous pits are present around the clypeus. The posterior margin of the head bears short hair. Eyes possess ~60–67 ocelli, mandible with ~22–26 fine teeth, which are arranged in rows. Mouthparts, are not dissected. Collum is dark green and covered by fine short hairs on the edges and the rest of the collum is glabrous.

**Gnathochilarium:** Ventral side with a few hairs, a thick tuft of bristles in the lingual lamella. A few sensory cones are present on the palpus. Central pad possesses very minute hairs. Some sensory cones possess pits and few are devoid of them.

**Antennae:** Antennae consist of six antennomeres and are covered by fine hairs. The apical one is oval-shaped and possesses more than 90 sensory cones. Sensory cones are blunt at the apex. Length of antennomeres in the order 1>2=3>4=5<6. The first antennomere is broader and bigger in size compared to other antennomeres. Sclerotised spots are absent on antennomeres.

**Thoracic shield:** A few isolated short hairs are present on the lateral extension of the thoracic shield shiny and finely punctured. Height is up to 18 mm, width 25 mm and breadth 8 mm.

**Tergites:** Anterior portion of tergite is rugose and punctured. The posterior region is smooth and polished. Anterior para-tergite depression consists of a few short hairs. A few ridges are found on para-tergite. Para-tergite apex projects posteriorly. The 8<sup>th</sup> tergite has 20–22 mm height, 12–14 mm width and 5–6 mm breadth. The ventral sides of tergites are dominated by setae and a series of sclerotised nodules at the brim, which helps to prevent the entry of dust and pathogens.

**Endotergum:** Two rows of marginal bristles covering three-fourths of the distance to the edge of the margin. The internal region possesses thick short spines as well as a few isolated lengthy bristles. No inner cuticular impressions are found.

**Anal shield:** Rounded and densely punctured with small hairs. The ventral side possesses 2 black locking carinae on each side. Anterior carinae are double the length of the posterior one. Distinct suture is present between the carinae representing the border of the 13<sup>th</sup> segment fused with anal tergite. An invagination is visible in the region where the suture reaches the margin. Five annular rings are found on the ventral side, which are covered by very fine short hairs. Four annular rings are longer and the remaining one is small.

**Legs:** Legs are dark-greenish, tarsi 1–2 with apical and 3 ventral spines, 3–9 with 6–11 ventral spines and 10–21 with 11 ventral spines. First two pairs of legs with apical spines and the remaining pairs with weakly curved claws. Tibia is covered with fine hairs.

**Stigmatic plates:** Plate has a broad base narrow blunt apex lobe with fine hairs. Lobe is slightly short and the apex curved towards coxa.

#### 4.5.1. Male sexual characters

**Gonopore:** Gonopore is present on 2<sup>nd</sup> pair of legs. It is covered with a single spherical sclerotised plate covering one-fourth portion of the coxa. A cluster of hair spread on the apical part of gonopore.

**Anterior telopods:** The first podomere possesses two stridulation ribs, the lower rib is longer and thicker than the upper one. Second podomere is broad, tibia and tarsus coalesced, tibia has superior cone-shaped lappet, tarsal part of 4<sup>th</sup> podomere with 2 flat lappets and edges are covered by short hairs. The anterior telopods curved and attained a horseshoe shape. The final podomere possesses numerous nubs and sclerotised spots.

**Posterior telopods:** Telopod syncoxite consists of very few hair covers. Femoral processes club-shaped, tibia with two white lappets and a line of numerous tubercles. The first podomere consists of sparse hairs. The movable fingers are dark, thick at the base and curved at the apex. Movable finger possesses numerous sclerotised spots. The first lobe is larger and thicker compared to the second one. The fixed finger has crenulated teeth in a row (~18). The inner horns of the syncoxite have pointed tip. Tip of the black inner horns curved outwards.

#### 4.5.2. Female sexual characters

**Vulva:** Coxae of 2<sup>nd</sup> pair of leg consists of the vulva and it is large, shields two-third of coxal portion. The operculum is broad as well as long. The mesal plate is long, broad at the base, which is extending beyond operculum. The anterior margin is devoid of indentation. The exterior and an inner plate of the vulva under the operculum surrounded the basal margins of the operculum shields with thick hairs at the apical part. The left and right mesal plates are hooking towards coxa. The right mesal plate with small invagination is found in the mesal region. The SEM studies have shown that a sub-anal plate with a washboard possesses three stridulation ribs on one side as well as four on another side.

#### 4.5.3. Distribution and ecology

**Distribution:** This species is commonly found in the forest of the Kodagu region of Western Ghats and its density is moderate in this region. This region receives good rainfall and consists of evergreen as well as semi-evergreen forests rich in tree species like *Artocarpus hirsutus*, *Euodia lunuankenda*, *Syzygium cumini* and *Terminalia tomentosa* and provides sufficient litter strata throughout the year. Collected regions were slope with thick vegetation. It is common near the trenches beside the roads with sufficient leaf litter.

**Life history and intraspecific variation:** Nearly 900 eggs per female were found during the post-monsoon season. The eggs are pale-yellowish and their size ranges from ~1.5–2.5 mm. Eggs are distributed from the region of the vulva up to the washboard in the abdomen. Male is smaller than female and most of the collected juveniles have well-developed telopods and washboards. Colour variations are seen between the individuals of this species. Compared to adults, juveniles are dull-colored and less active.

**Conservation:** Presently these species have distribution in the Makutta and Karike regions of Western Ghats. At present, forest cover is good and with less human activity, but activities like road, dam and railway track construction may threaten this species in the future. At present no conservation measures are enforced and also people are the least concerned about soil arthropods. More human attention as well as protective measures are necessary for the conservation of these endemic ecological entities.

**4.6. *Arthrosphaera hendersoni* Attems 1936 (Figure 6a and 6b)**

**Locality:** Normal locality of this millipede was the basins of *Areca* and coconut trees in Uppala, southwest coast of India (12°41'N, 74°56'E). Litter depth was 2–3 cm with a temperature of 29°C. The specimens are preserved in the zoological museum of Mangalore University, Karnataka, India (MUAZPMAh-06).

**Diagnosis:** The colour of the animal is ivory with a brownish tint and the posterior margin is pale-brownish, each tergite has a black irregular patch and the thoracic shield is brown. Pygidium has a black patch that almost covers the surface. Individuals possess continuous stretch of black irregular patches on both anterior sides of tergites except on the thoracic shield, which is clearly visible from juvenile to adult.

**Body length:** Male has a length up to 40.1 mm and female is up to 44.6 mm, weight varies from 6.6–9.4 g. Breadth ranges from 17.2–24.2 mm. Male widest axis ranges from 22.1–30.5 mm and female 23.4–30.9 mm. The narrow axis of males varies from 19.5–24.6 mm and females ranges from 21.5–27.0 mm. Females are slightly bigger than males.

**Habitus:** Medium size individual and anterior margins possess fine hairs. Tergite is finely punctured with a characteristic black irregular patch on the anterior region of tergites.

**Coloration:** Brownish-yellow to greenish-yellow, while a few with ivory-green coloration. The posterior margin of the tergite is black and a few dark brown small spots on tergites. Black patches are clearly visible on the anterior border of tergites. Collum is the black, head, antennae are deep green, legs are yellowish-green and anal shield is black in the middle and laterally brownish-yellow.

**Head:** Hairs are present on the anterior margin and around the clypeus. The rest of the head is smooth with small with a few isolated setiferous pits. Eyes are with ~66–70 ocelli. The region between the head and collum has a hook-like projection. Long hairs are found at the posterior end and a conspicuous tuft of bristle occupies the region towards the collum. Mandible with ~5–6 pectinate lamellae, the teeth number of pectinate lamellae decreases from apical to proximal. The molar plate has processes separated by a notch.

**Collum:** Single row of short hairs on the anterior edge and a few isolated long hairs on the posterior margin are clearly visible.

**Thoracic shield:** The colour mimics the tergite and row of short hairs found on the anterior margin. Lateral extensions have pits and numerous hairs. The anterior rim of the lateral extension is not broad and a ridge is seen along the lateral side.

**Antennae:** The antenna possesses six antennomeres. Antennomeres are deep green with yellowish-brown margins in the posterior region and the apical disc is light yellow. The first antennomere is broader than the remaining ones with numerous sclerotised spots. Length of antennomere in the order: 1>2<3>4=5<6. The 6<sup>th</sup> antennomere is the longest and shoe-shaped along with more than 116 sensory cones. Hairs are found in between sensory cones. Antennomeres are covered by thin long bristles.

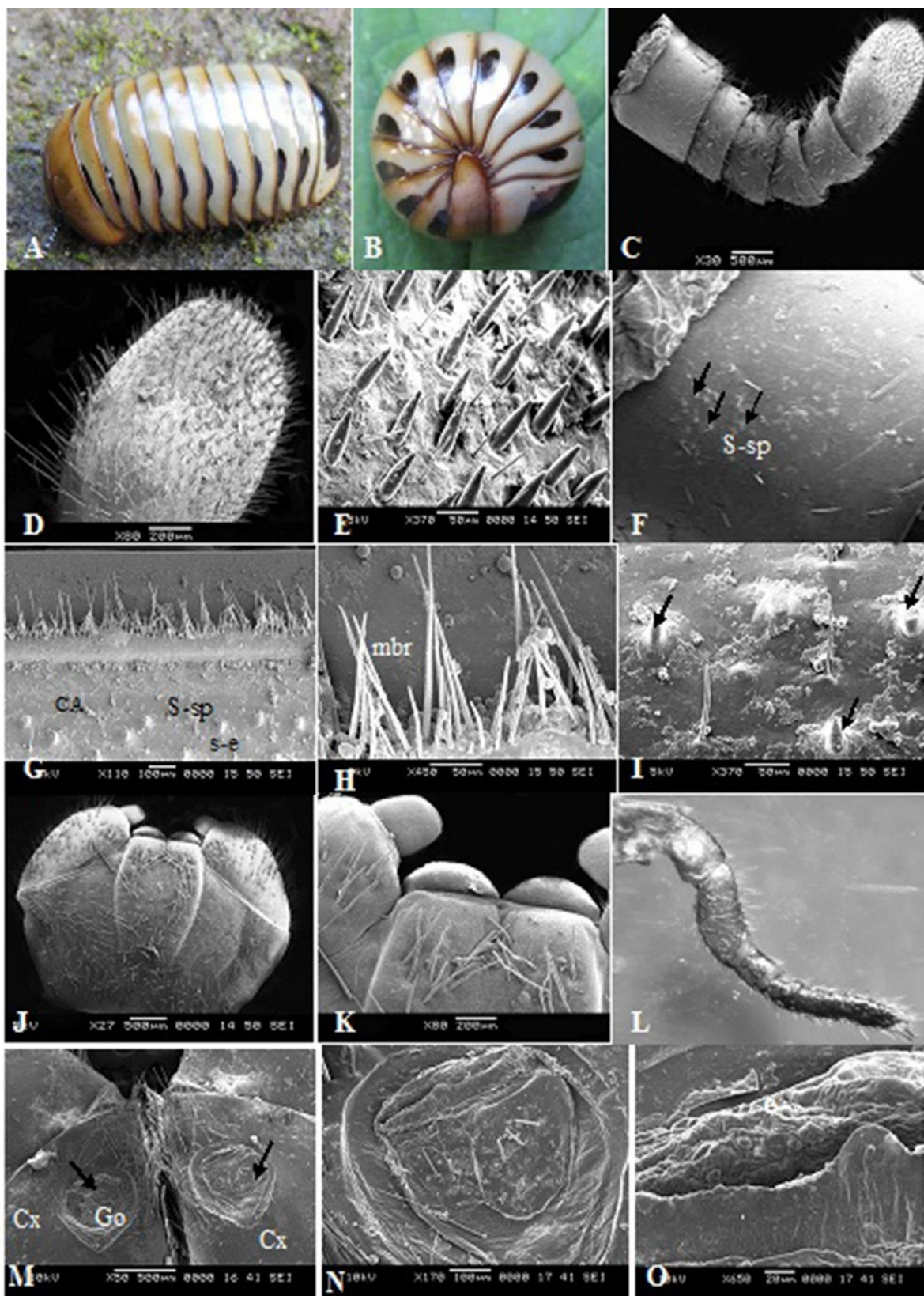
**Gnathochilarium:** Ventral side has several bristles and very few on lingual lamella. Central pads have a few isolated sensory cones.

**Tergites:** Anterior half of the tergites are finely punctured and pubescent. Para-tergite depression has a tuft hair cover. The posterior margin of tergites has a single row of fine hairs. Tips of posterior para-tergite extend posteriorly. The upper margins of sternite are round and completely covered by long hairs. Eight tergites have a width of 5 mm, a height of 11–12 mm and a length of 18–19 mm.

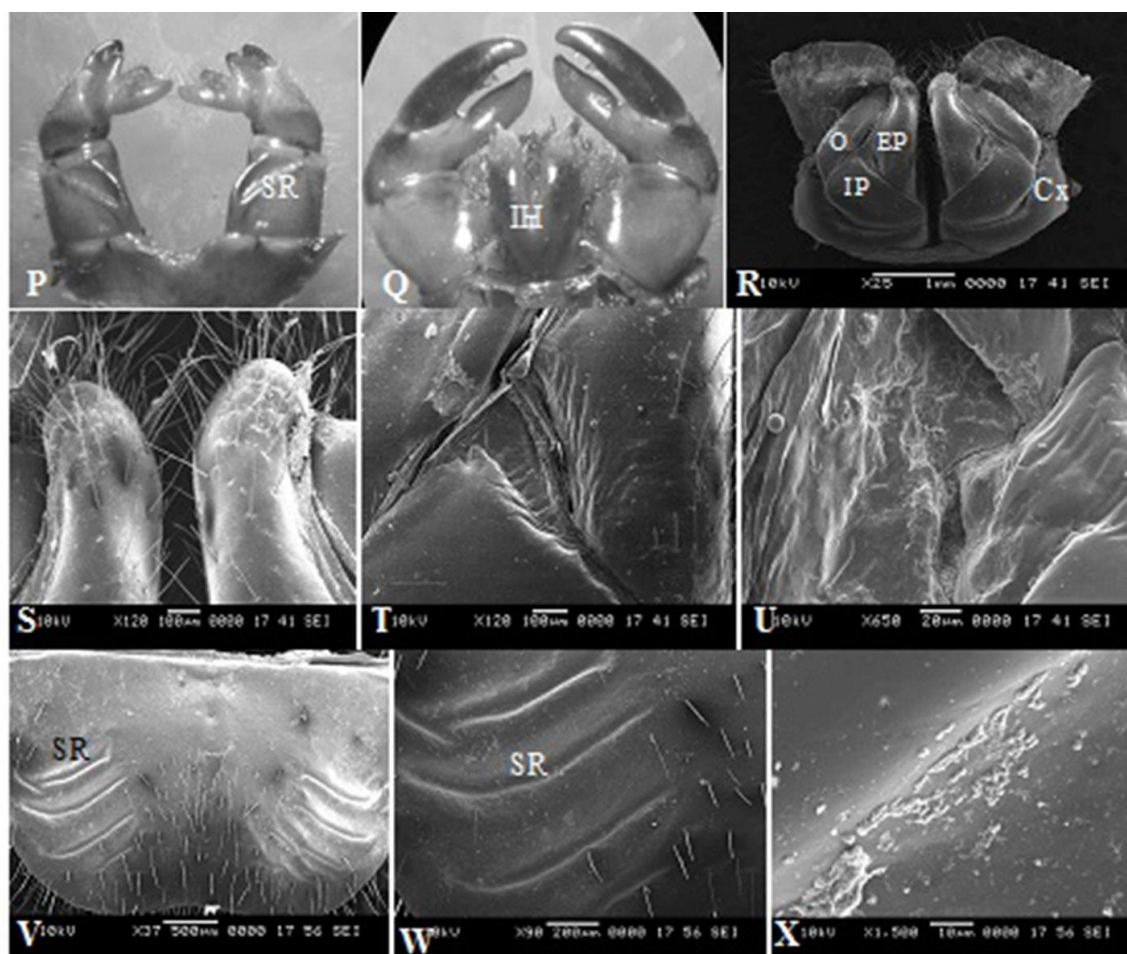
**Anal shield:** The anal shield is lightly saddle-shaped and gradually tapering towards the margin. Two black locking carinae on either side, the anterior one is similar to tergite and the posterior carina 2–3 times longer compared to the anterior one. The posterior carina is nearer to the margin compared to the anterior one. A suture is present between the carinae, representing the border of the 13<sup>th</sup> segment fused with the anal tergite. Small conspicuous invagination is found in the region where the suture meets the anal tergite margin. At the ventral side of anal tergite, 5–6 annular rings are present and it is covered by fine short hairs. The dorsal side was punctured with a few isolated fine hairs.

**Legs:** Tarsi of 1–2 with apical spine and ventral spines and mostly covered by fine hairs. The apical spine is a little longer with sharp tips. The remaining tarsi have 8–9 ventral spines and strongly curved claws. The prefemur and femur of most of the legs have dark reniculated spots. The 9<sup>th</sup> leg has the coxal lobe. Coxae of all the inside margin of the legs shielded by a patch of lengthy hairs.

**Stigmatic plates:** Lobe is almost triangular and it is covered by long and short hairs. The apical portion of the plate is hooking towards the prefemur.



**Figure 6a.** *Arthrosphaera hendersoni* Attems. **A**, moving animal; **B**, conglobated animal; **C**, right antenna; **D**, shoe-shaped last antennomere; **E**, sensory cones on distal antennomere; **F**, first antennomere with sclerotised spots; **G**, endotergum overview; **H**, posterior margin; **I**, Internal area of endotergum (arrows, spines); **J**, gnathochilarium ventral side; **K**, palpus; **L**, leg. **Male sexual organs**: **M**, holotype, second coxa with male gonopore (arrows, gonopore), **N-O**, the surface of gonopore.



**Figure 6b.** *Arthrospira hendersoni* Attems. **P**, anterior telopods (top view); **Q**, posterior telopods (top view). **Female sexual organs:** **R**, vulva (details); **S–U**, the apex of inner plate of the vulva; membranous folding; **V**, washboard; **W**, stridulatory ribs of washboard; **X**, the surface of stridulatory ribs.

#### 4.6.1. Male sexual characters

**Gonopore:** Gonopore is shielded by a single undivided oval-shaped sclerotised plate, which covers nearly one-fourth of the coxa. Thick bristles are found in the apical region and a few short fine hairs are found on the entire region of coxae of 2<sup>nd</sup> pair of legs.

**Anterior telopods:** The first podomere has two stridulatory ribs. The 2<sup>nd</sup> joint has a cone-like femoral process, which surpasses the third podomere. Second podomere margins consist of 10–12 sclerotised spots with a few isolated short hairs. The last podomere has an apical lobe and a lateral flat lobe, which is covered by short hairs. Margins of the first segment have hairs and surface glabrous. The final podomere consists of sclerotised spots and ribs at the posteroapical region. Right and left segments of the anterior telopod hook with each other and attain horseshoe shape.

**Posterior telopods:** Posterior telopods are syncoxite with triangular lobe-like projections. Elongated movable finger weakly curved towards the fixed finger. The movable finger has two lappets, and the mesal one is thicker and larger than the apical one. The tips are hook-shaped. The movable finger has a row of crenulated teeth (~14–16). The fixed finger is shorter compared to the movable finger and facing towards the latter. About 130–140 sclerotised spots are found on mesoapical region of the fixed finger except at the base. The inner horns have pointed tips and apical regions are bent at 45°. A tuft of hairs is present on the apical portion of the inner horn and facing outwards. Very few isolated sclerotised spots are found on the apical region of inner horns.

#### 4.6.2. Female sexual characters

**Vulva:** Second pair of legs with coxal lobe, vulva large covers three-fourths of coxal length. The operculum is long, not broad and neither subreniform. The mesal plate is long, slightly thin extending fairly beyond the coxa and operculum. The apical portion is covered with short hairs. The left mesal plate is slightly longer and straight but the right one is hooking towards pre-femur. The operculum has a few isolated sclerotised spots and fairly covered by hairs. A deep notch is found on operculum which covers three-

fourths of its length. Sub-anal plate with washboard bears 4 stridulation ribs on one side and 5 on the other. Three of them are long, and well-developed and the remaining ones are short and thin.

#### 4.6.3. Distribution and ecology

**Distribution:** These millipedes were recovered from the Uppala regions on the West coast of India. These animals are abundant in mixed plantations, which receive good rainfall and farmyard manure. The major plantation crops are *Areca*, *Cocoa*, coconut and banana. Nearly 20–30 years of organic farming along with sprinkler irrigation in summer seasons helped these millipedes to inhabit this location of the coastal region. Juveniles are active till December and most of the females dissected from this place showed eggs >600 and during post-December, these millipedes start hibernation.

**Intraspecific variation:** The body length and size of males and females are fairly similar. Most of the recovered juveniles possess well-developed reproductive systems. Juveniles are dark brown compared to light-colored adults. Colour variations are evident between males, males and females, and some of them are light-brown with a few isolated dark-brown irregular spots. Some have an ivory colour and black patches at the anterior border. Juveniles consist of regular black patches on their anterior edge.

**Conservation:** The fate of these animals depends on the organic farming and irrigation of mixed plantations in the coastal regions. The use of herbicide and Bordeaux mixture may deteriorate this millipede eventually in the future. Sustainable agricultural practices along with organic farming may help this millipede to sustain in the coastal areas.

#### 4.7. *Arthrosphaera magna* Attems 1936 (Figure 7a and 7b)

**Locality:** Collected from mixed plantations of Adyanadka (12°41'N, 75°6'E), the foothills regions of Western Ghats. They are abundant in the mixed plantation base with litter depth of 2–4 cm and temperatures of 27–29°C. The specimens are preserved in the zoological museum of Mangalore University, Karnataka, India (MUAZPMAM-07).

**Diagnosis:** Length up to 55 mm and weighs 15 g. Deep yellowish-brown with a yellow stripe on the posterior border of each tergite. The antennae and legs are olive green. The terminal disc of the antenna is slim, oval and oblique. The pygidium is slightly bell-shaped with a distinct lateral notch. The marginal thickening of the thoracic shield is equally thick and the anterior border is hairless. Collum has a few hairs on the edges.

**Body length:** Male has a length up to 55 mm and female up to 43 mm. Weight varies from 5–14.4 g. Breadth ranges from 16–27 mm. Male widest axis ranges from 22–33 mm and in females 20–27 mm. The narrow axis of males varies from 18–28 mm and in females 19–23 mm.

**Habitus:** Medium size animals and the marginal bristles of tergites are not extending beyond the border. Tergite is densely punctured and the anterior edge of tergite has small granules.

**Coloration:** Tergites are deep-brown with the posterior yellow margin forming a narrow stripe. Head and collum have chestnut or yellowish-brown. The antennae and legs are olive green. The pygidium is dark brown in the middle laterally brownish-yellow.

**Head:** Head and clypeus are sparsely punctate. Eyes possess ~81–86 ocelli. Long hairs are found at the posterior margin. Mandible has one step pectinate lamellae with four teeth.

**Collum:** Anterior and posterior margin with puncture and rest of the surface is not punctured.

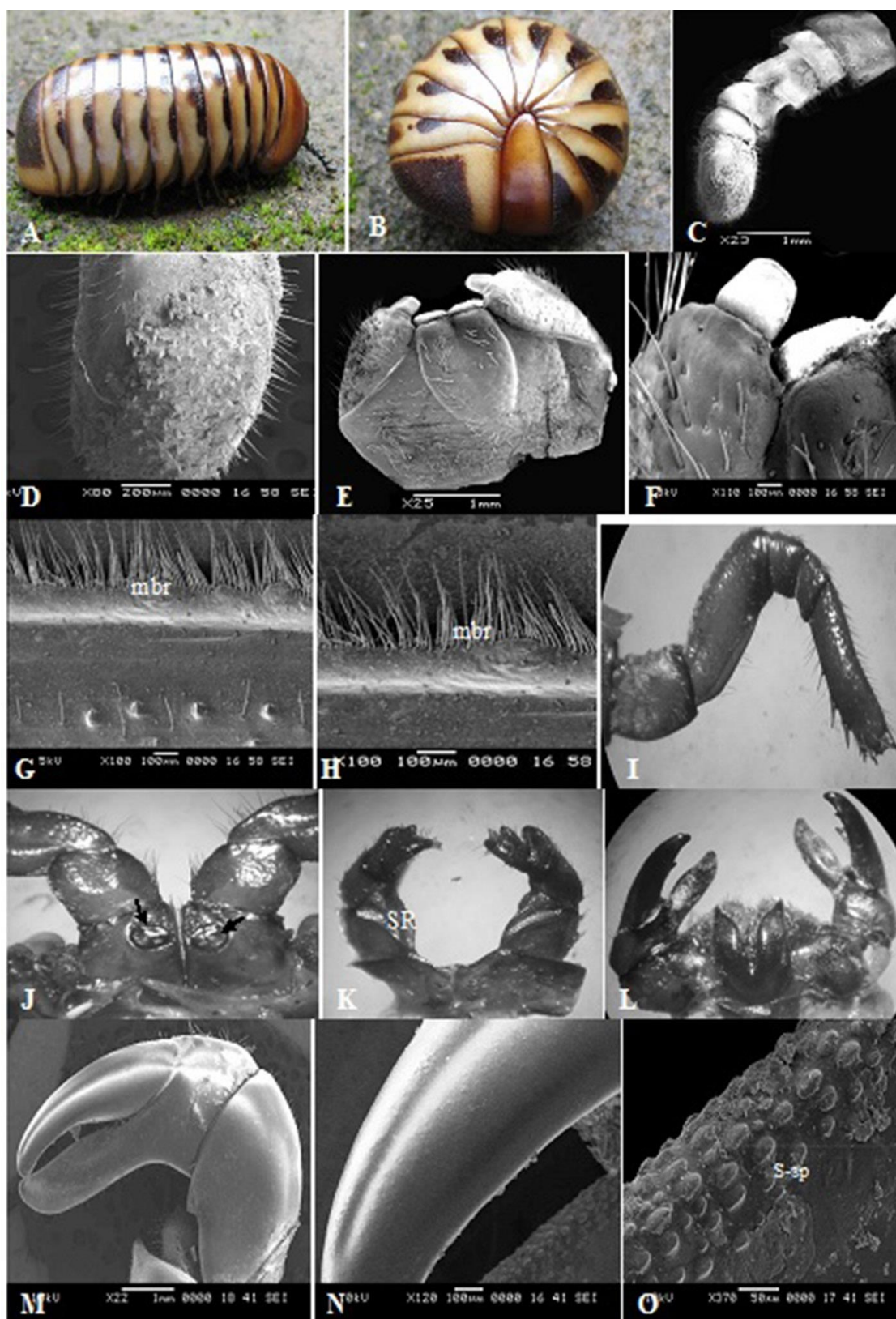
**Thoracic shield:** Colour mimics the tergite, polished, not punctate and marginal grooves are absent near the eyes. The lateral part of the grooves possesses fine hairs and marginal thickening is equal. The anterior portion has a few scattered punctures with fine hairs.

**Antennae:** The antenna possesses six antennomeres. Antennomeres are olive-green and the male has expanded apical disc. The terminal disc is narrow, oval and oblique. Over 90 sensory cones are present on the terminal disc. First antennomere is broader than the other. Length of antennomere: 1>2<3>4>5<6. Hairs are present between the sensory cones.

**Gnathochilarium:** Ventral side has many bristles and a few on lingual lamella. Central pads and palpi have a few isolated sensory cones as well as pits.

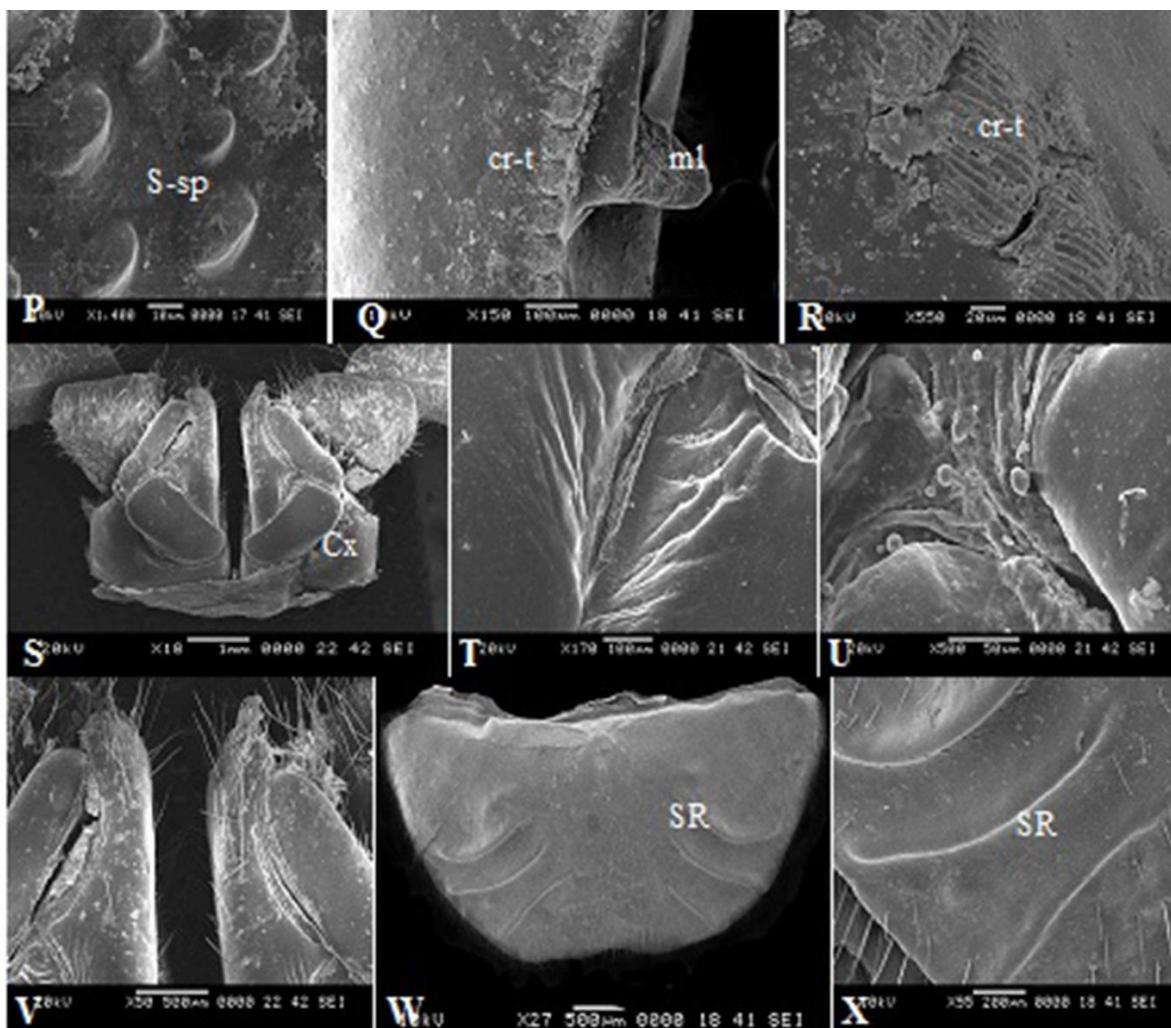
**Tergites:** Anterior end of the tergites possess small granules, half of the tergites are densely punctured and hairy. The posterior margin has a few punctures and the posterior half is smooth and shiny. Marginal bristles are not extending over the border. The width of the 8<sup>th</sup> tergite is 4–5 mm, height 20–21 mm and length 12–13 mm.

**Endotergum:** Two rows of marginal bristles cover almost the entire length. A few isolated spines in the central area are thick and stout. Isolated long bristles are found in between spines.



**Figure 7a.** *Arthrosphaera magna* Attems. **A**, moving animal; **B**, conglobated animal; **C**, right antenna; **D**, sensory cones on distal antennomere; **E**, gnathochilarium ventral side; **F**, palpus; **G**, endotergum overview; **H**, posterior margin; **I**, leg. **Male sexual organs:** **J**, holotype; second coxa with male gonopore (arrows, gonopore); **K**, anterior telopods (anterior view); **L**, posterior telopods (top view); **M**, right chela of posterior telopod; **N–O**, sclerotised spots on movable fingers.





**Figure 7b.** *Arthrospira magna* Attems. **P**, sclerotised spots on the movable finger; **Q–R**, a row of crenulated teeth on the fixed finger with membranous lobe. **Female sexual organs:** **S**, vulva (details); **T–V**, membranous folding and apex of inner plate of the vulva; **W**, washboard; **X**, stridulatory ribs of washboard.

**Anal shield:** Slightly bell-shaped and densely punctured, sometimes many punctures united to form shallow depression. The anterior zone is densely punctured with hairs. Two black locking carinae exist on either side. The posterior carina is closer to the margin than the anterior carina. A suture is present between the carinae. A small conspicuous invagination is seen at the end of the suture margin. The ventral side of anal tergite possess 5 annular rings, of which 2 are small and 3 are long and covered by fine short hairs.

**Legs:** Tarsi of 1–2 with apical spine and 3–4 ventral spines and mostly covered by fine hairs. The remaining tarsi possess 8–11 ventral spines and a curved claw. The margin of coxae covered with many long bristles. The 9<sup>th</sup> leg has small teeth. Coxae of the legs at the inner side margin shielded by lengthy hairs.

**Stigmatic plate:** Lobe is almost triangular and it is covered by long and short hairs. The apical portion of the plate is hooking towards pre-femur.

#### 4.7.1. Male sexual characters

**Gonopore:** The gonopore is without a coxal lobe and covered by a single undivided slightly round sclerotised plate up to one-fourth of the coxa. A few short fine hairs are found on the entire region of coxae of the second pair of legs.

**Anterior telopods:** The first podomere has two stridulatory ribs. Femoral processes are short and blunt, and are situated behind tibio tarsus. Tibia as well as tarsus are distinctly separated, the tibia has a superior round lobe becomes narrowed and cylindrical with long thick bristles at the apex. Small knob and spines are found on the posterior side. Second podomere margins consist of a

few sclerotised spots and a few isolated short hairs. Margins of the first segment possess hairs and surface glabrous. Right and left segments of anterior telopods hook each other and attain horseshoe shape.

**Posterior telopods:** Coxal horns are large and thick at the base, thick short hairs are present in the mesoapical region. Apex is rounded and consists of a dark-coloured claw. Femoral processes are longer than the tibia and crenulated teeth are present on the inner side. The tibia consists of 2 short broad lappets, a posterior edge with numerous rounded tubercles. Behind the tibia a few rounded tubercles are present. Movable fingers possess about 16–17 crenulated teeth and fixed fingers consist of numerous sclerotised spots.

#### 4.7.2. Female sexual characters

**Vulva:** The second pair of legs consist of the coxal lobe. The vulva is large and shields three-fourths of the length of the coxa. The operculum is large and broad. Long mesal, slightly thin and extending fairly beyond coxa and operculum. The apical portion has short hair. The left mesal plate is slightly longer and straight but the right one is hooking towards pre-femur. The operculum has a few isolated sclerotised spots and is fairly covered by hairs. Sub-anal plate with washboard bears 3 stridulation ribs on either side are 2 are long, well-grown and remaining is short as well as thin.

#### 4.7.3. Distribution and ecology

**Distribution:** These millipedes were abundant in the mixed plantations of Adyanadka, foothill region of the Western Ghats. Plantations are organically maintained and receive farmyard manure, green manure and mixed leaf litter with adequate irrigation. The major cultivated plantation crops include *Areca*, *Cocoa*, coconut and banana. Nearly as long as 20 years of organic farming practices in these plantations resulted in the migration of *A. magna* from the forests to plantations and is active almost throughout the year except during peak summer. Most of females dissected from this locality showed more than 800 eggs during December.

**Intraspecies variation:** The body length and size of males are higher than females. Most of the recovered juvenile possesses well-developed reproductive systems. There is no major colour variation between males and between males and females. Juveniles are less active compared to adults.

**Conservation:** Future ecological services of these millipedes are depending on sustainable organic farming and irrigation, especially in the foothills of Western Ghats. The use of organic herbicides and Bordeaux mixture is common to fight against weeds and fungi. Except for organic farming, to date, no conservation measures are enforced to protect these millipedes. However, organic farming and irrigation practice has attracted these millipedes from the forest localities and most likely the local extinction may not occur. Such organic farming practices should be operated on a large-scale for the conservation of these millipedes.

#### 4.8. *Arthrosphaera versicolor* Pocock 1899 (Figure 8a and 8b)

**Locality:** Collected from the forest floors of Shimoga regions of Western Ghats (13°35'N, 75°48'E), which was associated with *A. disticta*. The number of these animals is very less in this region (ratio of *A. versicolor* vs. *A. disticta*: 1:500). The depth of litter was 3–6 cm and the temperature was 27°C. The specimens are preserved in the zoological museum of Mangalore University, Karnataka, India (MUAZPMAv-08)

**Diagnosis:** Small size animals and tergites are covered with variegated black spots. The washboard has numerous rudimentary ribs. Antennae are dark and greenish-brown with the shoe-shaped apical disks. Numerous sclerotised spots are found in the first antennomere. Endotergum consists of double row of marginal bristles that attain half of the distance towards the margin. The pygidium is slightly bell-shaped and 6 annular rings are found on the ventral side. Anterior telopods have a single stridulation rib.

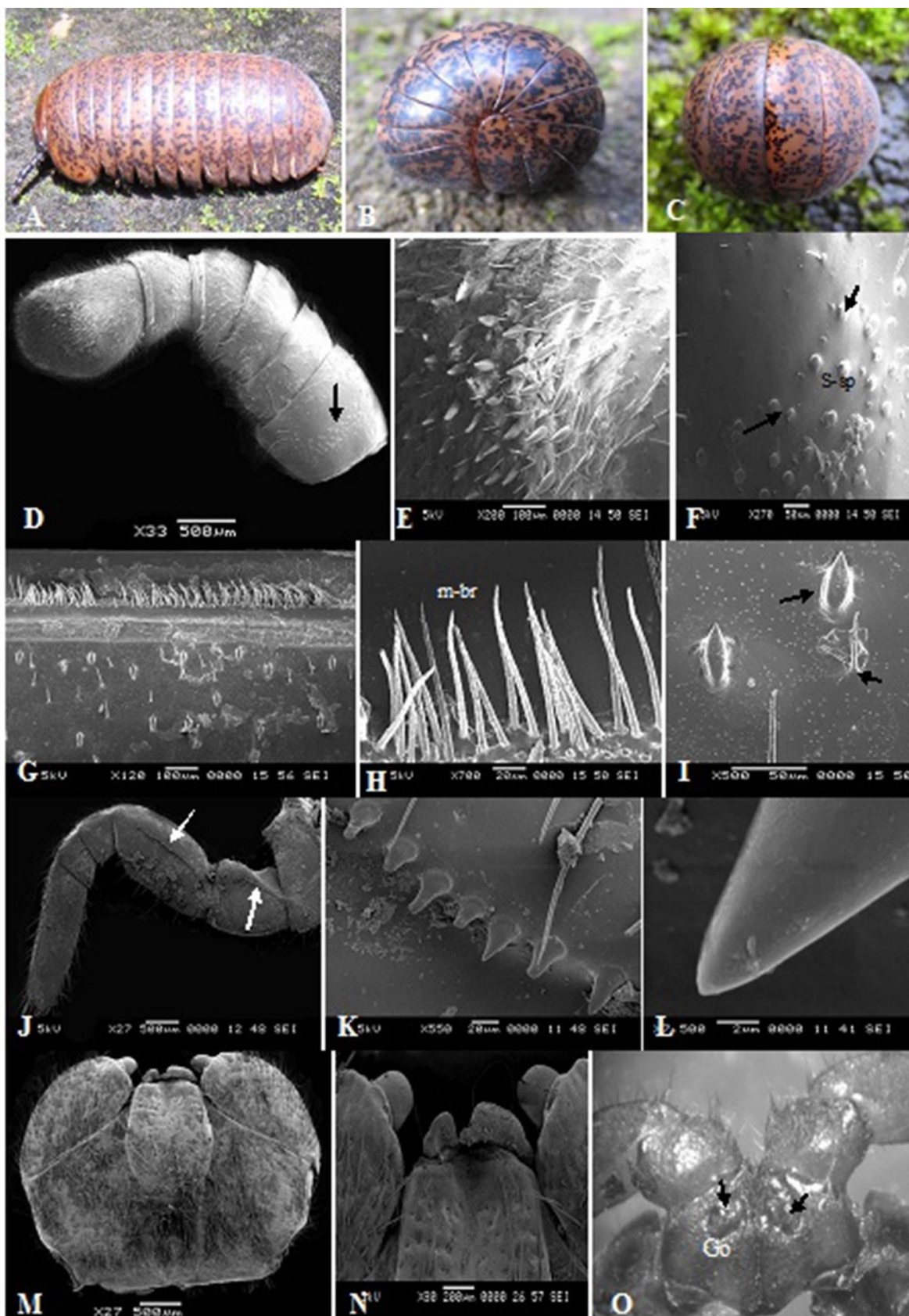
**Habitus:** Small size brownish variegated black-spotted millipede. Like *A. disticta* no black spots were found on the anterior edges of each tergite. Black spots are distributed randomly.

**Coloration:** Smoky-brown coloration possesses irregular black patches and spots.

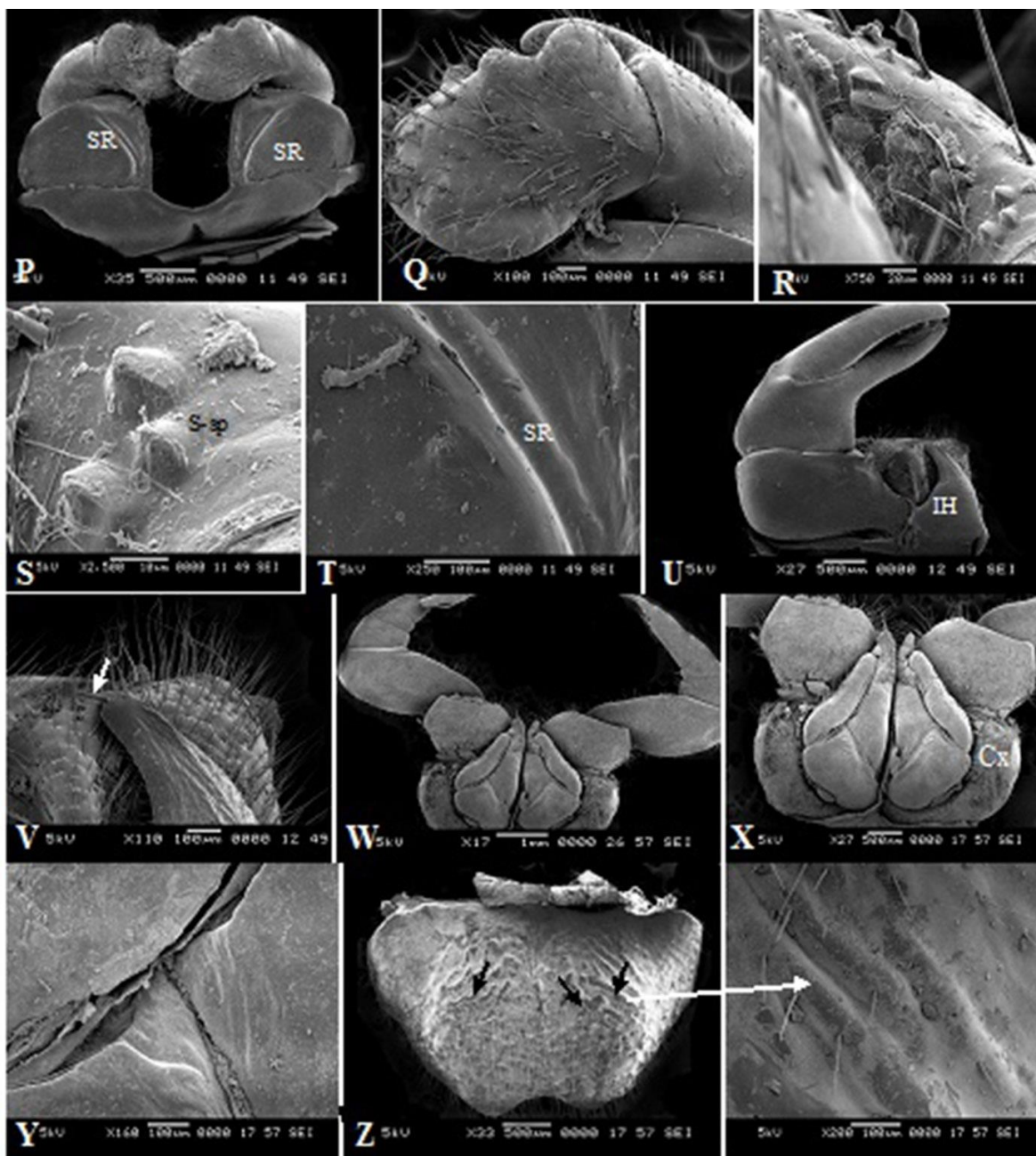
**Head:** Smooth, shiny and consists of sparse hairs. Eyes with ~70–80 ocelli and mandible have fine teeth of three rows with 8–12 teeth in each row. The antenna is dark greenish-brown with a shoe-shaped apical disk. Sparse hairs are present on all the antennomere. The length of antennomere: 1>2<3>4<5<6. The SEM analysis showed that the sensory cones are blunt ends. The number of sensory cones varies from 86 to 94. Many sclerotised spots are present at the base of the first antennomere.

**Collum:** Dark-brown possesses fine hairs on edges with variegated black spots.

**Thoracic shield:** Surface mimics the tergites, height 6.5 mm, width 12 mm and breadth 4 mm.



**Figure 8a.** *Arthrosphaera versicolor* Pocock. **A**, moving animals; **B–C**, conglobated animal; **D**, right antennomere; **E**, sensory cones on distal antennomere; **F**, first antennomere with sclerotised spots; **G**, endotergum overview; **H**, posterior margin; **I**, the internal area of endotergum (arrows, spines and setae); **J**, Leg (arrows, spines); **K**, a row of spines on prefemur and femur of the leg; **L**, individual spine; **M**, gnathochilarium ventral side; **N**, palpus. **Male sexual organs**: **O**, holotype, second coxa with male gonopore (arrows, gonopore).



**Figure 8b.** *Arthrosphaera versicolor* Pocock. P, anterior telopods (anterior view); Q, apical region of anterior telopod; R–S, sclerotised spots on final podomere; T, ribs on podomere; U, posterior telopod (anterior view); V, inner horn (arrow, spine). **Female sexual organs:** W–X, vulva (details); Y, membranous folding; Z, Washboard with rudimentary ribs (arrows).

**Tergites:** The surface is smooth, shiny and possesses black dots with a few hairs. Tips of tergites project posteriorly with a sharp point. The 8<sup>th</sup> tergite has 11–12 mm height, 5–7 mm width and 3–5 mm breadth.

**Endotergum:** Double row of marginal bristles reach half the distance to the edge of the margin. The internal portion has short spines with very few isolated long bristles. No inner cuticular impressions were seen.

**Anal shield:** The surface is shiny, slightly bell-shaped as well as the bottom exhibits a bell-like flare. The surface consists of sparse short hairs. The lower side carries 2 dark-brown locking carinae, the anterior doubles the size of the posterior. Anterior carina is partially curved towards margin of anal shield. Anterior carina is thick, and long and the posterior one is thick and stout. Six annular rings are found.

**Legs.** Greenish-brown, tarsi possess 12–13 ventral spines, first two pairs of tarsus have the apical spine. The femur has a small extrusion covered with hairs. Pre-femur and femur have an array of spines. Femur consists of ~40 spines and pre-femur with ~26 spines. The roles of these spines are unknown and it is assumed to be involved in stridulation.

**Gnathochilarium:** Central pad slightly bulged in the middle. Palpi have numerous sensory cones on their apex. The surface is covered with long hairs except for the apical portion of the central pad. Tufts of hair are present on the stipites.

**Stigmatic plates:** The plate has a triangular lobe with fine hairs. Lobe is short and the apex curved towards coxa.

#### 4.8.1. Male Sexual characters

**Gonopore:** Slightly bell-shaped anal shield covers the telopods. Gonopore is covered with small hair on the apical side. A single round sclerotised plate covers half of the height and half of the width of the coxa.

**Anterior telopods:** Harp with single rib and lateral edge of syncoxite close to the first podomere with very few isolated sclerotised spines. The second podomere process is triangular, pointing towards the third podomere. The anterior telopods curved each other and attain a perfect horseshoe shape. The final podomere has sclerotised spots and crenulated teeth, which have the main role is stridulation. The apical portion of the final podomere is expanded.

**Posterior telopods:** Movable fingers are thicker and hook towards the fixed fingers. The movable finger possesses ~16 sclerotised crenulated teeth with 2 membranous lobes. The first lobe is larger and thicker compared to the second. The tip of the fixed finger is blunt and a few hairs are found on both the fingers. Fixed fingers have numerous sclerotised spots. The first podomere possesses sparse hairs. The tip of the inner horns is black as well as curved outwards with a spiny tip. The inner lobe is quite flat and pointing inwards attaining almost a bowl shape.

#### 4.8.2. Female sexual characters

**Vulva:** Vulva is large and covers two-thirds of the coxa of second pair of legs. The operculum is thin and slightly intends middle and ends before the edge of the coxa. The external plate is short and broad, and covers isolated hairs at the base. The external plate and inner plate cover the basal margin of the operculum. The inner plate is long as well as fairly broad and surpasses the operculum. The tip of inner plate is hooking towards the coxa and covered with typical hairs. Clearly visible dark structure is found close to the suture of the vulva between the inner and external plates. Sub-anal plate with washboard has many rudimentary ribs and the entire surface is covered by hairs.

#### 4.8.3. Distribution and ecology

**Distribution:** This millipede was rarely found on the forest floor of the Shimoga region of the Western Ghats along with a high population of *A. disticta*. This region of Western Ghats consists of semi-evergreen forests and receives good rainfall. Tree species especially *Terminalia* provide sufficient litter strata and good shelter for the normal growth and propagation of *A. versicolor*. The sampling regions are disturbed mainly by roads and vehicular traffic.

**Life history:** This dull-colored millipede is slightly bigger than *A. disticta*. Females are bigger than males. Each female lays nearly 600–700 pale yellow eggs per season and the size of eggs varies between 1.3 and 1.6 mm.

**Conservation:** The density of this millipede is very sparse compared to its associate *A. disticta* in the same region. Roads and vehicular traffic is the major threat to their survival. Currently, no conservation measures are practiced in their locality. Most likely this millipede may be wiped off much earlier than *A. disticta* due to their low population. Education of local people around the habitat of this millipede may help to utilize their ecological services in semiarid agriculture in the Shimoga region.

## 5. DISCUSSION

Although the geological history of pill-millipedes reveals their evolution was as early as the pre-Jurassic period, most of the species are inadequately documented and described (Wesener et al., 2010). Studies during the late 1890s and mid-1930s by Pocock (1892, 1899) and Attems (1936) are insufficient to elucidate the characters more precisely and explanations for many important structures are missing. Examination of new characteristics as well as improvement of insufficiently described characters may open up new avenues to solve the taxonomic uncertainties as attempted by Wesener and VandenSpiegel (2009), and Wesener (2014) considered finer details of 89–100 characters in paleotropical and Australian pill-millipedes, respectively.

The size and colour of pill-millipedes vary drastically in *Arthrosphaera*. Individuals who exist in the forests are bigger than those inhabiting in plantations of the Western Ghats in India (Ashwini, 2003). Some millipedes showed increased body size especially the inhabitants in high altitude regions (Enghoff & Báez, 1993). The coloration is also a prominent character to be considered in pill-millipedes as it varies from one individual to another and is dependent on the location of existence molting stage. Similar to the present study, different species of Sphaerotheriida possessing attractive coloration have been reported from different parts of the paleotropics. For example, *Zoosphaerium* in Madagascar has an emerald-green; *Procyliosoma tuberculatum* in New Zealand has

maroon and *P. striolatum* has a black border; *Arthrosphaera fumosa* in the Western Ghats of India has black with ivory-white forms; Tanzanian pill-millipedes have orange with maroon as well as an emerald-green border; some pill-millipedes are black or brown, especially the *Procyliosoma lae* and *P. tasmanicum* (Wesener & Sierwald, 2005a, b; Kadamannaya and Sridhar, 2009).

The head of pill-millipedes embodies mouthparts and many sensory structures like antennae, Tomosvary organs and eyes as well. So far the Tomosvary organ's structure and functions are less clearly understood. Pill-millipedes are devoid of median eyes and a patch of ocelli was found and these are considered derivatives (or remnants) of compound eyes. The mouth consists of a pair of mandibles and a plate of gnathochilarium, the latter has fused the first maxilla (Henning and Mickoleit, 1986), while Kraus (1974) claimed that it is formed by the fusion of maxillae. Pygidium in Sphaerotheriida might have developed by fusion of at least two last pairs of segments (Verhoeff, 1928). VandenSpiegel et al. (2002) opined that endotergum is also known for species-specific characters in the genus *Sphaerotherium* in South Africa. The sclerotised ridges on the male harp may provide a grip on female legs during copulation (Wesener et al., 2011). The presence of grooves in the female washboard supports the notion that fusion of two separate plates occurred especially in *Arthrosphaera disticta*. Earlier studies on *Sphaeromimus* also suggested the fusion of ribs, which resulted in presence of sutures in the washboard (Wesener and Sierwald, 2005a).

Many of the morphological terms in pill-millipedes are ambiguous and inadequately explained (Wesener & Sierwald, 2005b). The sexual structures are important and they are likely species-specific, but they were not fully described. Anterior and posterior telopods with precise characteristics have a prominent role in separating species. The anterior telopods with stridulation ribs particularly on the first podomere is highly characteristic. Two stridulation ribs are seen in *Arthrosphaera carinata*, *A. dalyi*, *A. davisoni*, *A. fumosa*, *A. hendersoni* and *A. magna*, while it was represented by a single rib in *A. disticta* and *A. versicolor*. Comparisons of detailed morphological features of eight *Arthrosphaera* spp. studied are given in Table 1. The ribs are playing major role in stridulation, which leads to the mating sequence (Wesener et al., 2011). *Arthrosphaera fumosa* shares similarities in the posterior telopods with that of *A. davisoni*. At the caudal end of the female has a washboard and it plays a precise role in stridulation (Wesener & Sierwald, 2005b). The number of ribs varies between species and the aging of individuals plays a significant role in retaining the intact structure of ribs (Wesener & Sierwald, 2005a). For instance, rudimentary ribs are seen in *A. versicolor*, while the ribs are conspicuous in other species of *Arthrosphaera*.

**Table 1.** Comparison of morphological characteristic features of eight species of *Arthrosphaera* occurring in the Western Ghats of India.

	<i>Arthrosphaera carinata</i> (Fig. 1a and 1b)	<i>Arthrosphaera dalyi</i> (Fig. 2a and 2b)	<i>Arthrosphaera davisoni</i> (Fig. 3a and 3b)	<i>Arthrosphaera disticta</i> (Fig. 4a and 4b)	<i>Arthrosphaera fumosa</i> (Fig. 5a and 5b)	<i>Arthrosphaera hendersoni</i> (Fig. 6a and 6b)	<i>Arthrosphaera magna</i> (Fig. 7a and 7b)	<i>Arthrosphaera versicolor</i> (Fig. 8a and 8b)
Location (coordinates)	Adyanadka (12°41'N, 75° 6'E)	Ninthikallu (12°39'N, 75°26'E)	Kudremukh (13°12'N, 75°16'E)	Shimoga (13°43'N, 75°37'E)	Karikeri (12°27'N, 75°23'E)	Uppala (12°41' N, 74°56' E)	Adyanadka (12°41'N, 75°6'E)	Shimoga (13°43'N, 75°37'E)
Color	Glabrous, shiny-black with thin deep-brown posterior margin and it is conspicuous during movement and less clearly visible during conglotation	Olive-brown with reddish posterior margin	Black with a posterior yellow band	Olive-yellow, deep-red and brownish- black with variegated spots	Pale olivaceous with smoky-black posterior half	Brownish-yellow to greenish-yellow with black posterior margin and black patches are found on each side of tergites	Dark-brown with yellowish band at posterior half	Smoky-brown with irregular black patches and spots
Length (mm)	49	46.6	47.9	27	48.3	40.2	42.2	26
Molar plate	2	2	2	2	2 step	2 steps	1 step	1
Rows of teeth in pectinate lamella	4–5	5	7	6	7	6	4	6
Coxal lobe of legs	Present	Present	Present	Present	Absent	Present	Coxal tooth	Present
Hairs on collum	Single row of short hairs on anterior edge and a few isolated long hairs on posterior margin	Margins	Both borders possess hairs	Hairs found on borders	Anterior margin with a few hairs	Short hairs on anterior margin and long a few isolated hairs on posterior margin	Both border with hairs	Fine hairs on edges with variegated black spots

Width of thoracic shield (mm)	22–24	24–27	20–22	12–13	24–26	20	22–23	12
Anal shield shape and surface	Slightly bell-shaped	Rounded, densely punctured and pubescent throughout	Slightly saddle-shaped and surface with a few isolated short hairs	Ovenly convex and surface with a few isolated short hairs	Slightly rounded and closely puncture with a few short hairs	Rounded at the apex and gradually tapering towards margin with a few fine hairs	Slightly bell-shaped with shallow depressions (anterior region densely punctate with hairs)	Surface shiny, slightly bell-shaped and bottom exhibits bell-like flare
Anterior locking carinae	Long and fairly thick	Long and thick	Long and thick	Very long and thick	Very long and thick	Long and thin	Little longer and thick	Long and thick
Posterior locking carinae	Short and thin	Short and thick	Very short and thick	Short and thick	Short and slightly near to margin	Short and near to margin	Short and equal distance to margin	Short and thick
Number of annular rings on ventral side of pygidium	3–4	5	4	8, 6 <sup>th</sup> and 4 <sup>th</sup> annular rigs show a typical branching	5 (4 are long and 1 small)	2–3 equal length	4–5 (2 are small and 3 are long)	3
Leg	Tarsi of 1–3 with apical spine; 4 ventral spine; tarsi 4–8 with 8 ventral spines and weekly curved claw	Tarsi of 1–2 with apical spine; 2–3 ventral spines and mostly covered by fine hairs; remaining tarsi with 9–11 ventral spines and a curved claw	Tarsi 1–2 with 2 ventral spines; 3–9 with 13 ventral spines; 10–21 with 11 ventral spines	Tarsi 1–2 with 2 ventral spines; 3–9 with 12 ventral spines; 10–21 with 10 ventral spines	Tarsi of first two pair of legs with 3–4 ventral spines	Tarsi of first two pair of legs with 1–2 ventral spines	Tarsi of first two pair of legs with 3–4 ventral spines	Tarsus with 1–13 ventral spines (first two pairs of tarsus with apical spine)
Endotergum and marginal bristle	Double row of marginal bristles covers half the distance to the margin	Covers half of the length	Bristles reaching half distance to edge of margin	Double row of marginal bristles reaching three-fourth distance to edge of margin	Covers nearly three-fourth	Extending to half of the distance to edge of margin	Extending to margin	Double row of marginal bristles (reaching half of distance to edge of margin)
Relative length of antennomere	1>2=3>4=5<6	1>2=3>4=5<6	1>2=3>4=5<6	1>2=3>4=5<6	1>2=3>4=5<6	1>2<3>4=5<6	1>2<3>4>5<6	1>2<3>4<5<6
Number of sensory cones on right antennae of male	~100	More than 78	~93	More than 110	~94–98	~116	~90	~86–94
Gnathochilarium	Ventral side with many bristle and very few on lingual lamella	Many hairs are randomly distributed on posterior surface	Ventral side with many hairs, very few hairs on lingual lamella	Gnathochilarium ventral side with many bristle, thick tuft of bristles in lingual lamella and with a few sensory cones on palpus	Hairs mainly found on apical region	Normal hairs on lingual lamella	Very few isolated hairs on lingual lamella	Many bristles on ventral side and numerous cones on lingual lamella
Para-tergites of posterior tip	Projecting posteriorly	Projecting posteriorly	Posterior projection of para-tergite tip is conspicuous	Projecting posteriorly	Projecting posteriorly with sharp pointed tip	Projecting posteriorly with pointed tip	Slightly projecting posteriorly	Projecting posteriorly
Male gonopore plate	Covers one-fourth of coxa and covered by single divided oval-shaped sclerotised plate	Single undivided, round, sclerotised plate and covers nearly one-fourth of the coxa	Gonopore covered with single, undivided and round sclerotised plate	Gonopore covered with single, undivided and round sclerotised plate with a membranous folding inside	Sclerotised plate small and round	Sclerotised plate slightly oval-shaped	Sclerotised plate is round	Single round sclerotised plate (covers one-half of height and one-half of width of coxa)

Nature of tibia and tarsus of anterior telopod	Separated	Separated	Separated	Separated	Coalesced	Separated	Quite separated	Separated
Relative size of vulva	Vulva is well-developed, large and covers three-fourth of length of coxa	Vulva larger covers three-fourth of length of coxa	Covers most of the coxal part	Covers the most of the coxal part	Covers two-third of coxa	Covers almost entire portion of coxa	Covers the two-third of coxa	Vulva is large and covers the two-third portion of coxa of second pair of legs
Nature of operculum	Operculum long	Operculum long and thin	Operculum long	Operculum short	Very broad and long	Long, not broad and ending slightly below the apical margin of coxa	Larger and broader	Operculum is fairly thin
Form of operculum	Slightly disc-shaped and shallow intended in the middle	With a few isolated sclerotised spots and fairly covered by hairs	Without any central invagination	Deeply sulcate at the mesoapical portion	With single blunt lobes	With single blunt lobes and weak invagination in the middle	With single blunt lobe with strong invagination in the middle	Shallowly intends middle and ends before the edge of the coxa
Number of stridulation ridge on harp	2	2	2	1	2 (stridulation ridges)	2 (almost equal stridulation ridges)	2 (one long and one short)	1
Number stridulation ridge on washboard	3	4	4 on each side	One on each side	Three on one side and four on another side	Four on one side and five on another side	Three on each side	Many rudimentary ribs

## 6. CONCLUSION

The present study has strengthened the characteristics of *Arthrosphaera* spp. of the Western Ghats of India based on detailed morphological features. Comparison of the specific organs of pill-millipedes across the species or genera will be highly valuable in refining further classification. There is a direct relationship between the morphology and behavior of the pill-millipedes. For example, i) locking carinae on pygidium and thoracic shield in conglobation; ii) ribs on telopods and washboards in stridulation; iii) telopods, gonopore as well as vulva in copulation. Similarly, the pattern, as well as precise changes taking place in pill-millipedes during the molting process may provide additional clues to elucidate genus- or species-specific differences. Besides, changes in coloration will also assume importance to compare the genera and species in different adult stages as well as molting. Finally, in view of future investigations, it is necessary to link the morphological characteristics of pill-millipedes of *Arthrosphaera* with their adaptation and behavior by considering effective molecular tools.

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### Ethical approval

Eight endemic *Arthrosphaera* (pill-millipedes) were collected from the Western Ghats of India. The ethical guidelines are followed in the study for sample collection & identification.

### Conflicts of interests

The authors declare that there are no conflicts of interests.

### Data and materials availability

All data associated with this study are present in the paper.



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