Expansion of geographic and host ranges of *Formicococcus polysperes* Williams (Hemiptera: Pseudococcidae) in India with small cardamom (*Elettaria cardamomum* (L.) Maton) as a new host record

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Abstract

The geographic and host range of *Formicococcus polysperes* Williams (Hemiptera: Pseudococcidae) has expanded in India since its first collection in 1949. Through this paper, the first occurrence of the root mealybug *F. polysperes* on small cardamom [*Elettaria cardamomum* (L.) Maton; Zingiberaceae] is reported in India. The infestation was initially noticed on a yielding cardamom plantation with four-year-old plants of the variety 'Green Gold' in the root zone, particularly on the fresh white roots, in the Ayyappankovil panchayat of Idukki district, Kerala, India. Aggregation and feeding by nymphs and adults cause distorted shape, browning, and shrinking of the roots, as well as yellowing of the leaves, resulting in a sick appearance of clumps, which leads to fewer tillers and unhealthy panicles. The species *F. polysperes* has spread across the country's length and breadth, and it was gathered from ten states in India, with several collections occurring in the southern regions (Kerala and Karnataka) and the northeastern areas (Meghalaya, Arunachal Pradesh, and Nagaland). An updated host list reveals that the mealybug infests 23 host plants across 17 families in India, of which ten host plants possess considerable economic importance. In the occurrence of outbreaks and the ensuing proliferation of this harmful pest on economically important crops like cardamom, identification and timely reporting are essential for effective management; thus, field diagnostics, slide-mounted features, and DNA sequences are provided with the assistance of field and mounted mealybug photomicrographs and by adopting appropriate molecular tools.

Introduction

Small cardamom [*Elettaria cardamomum* (L.) Maton; Zingiberaceae] is widely cultivated in the high-altitude hilly areas of the southern Western Ghats, predominantly between 900 to 1600 m above MSL, for its spicy aromatic capsule (Ravindran, 2002; Murugan et al., 2009). India, the second-largest producer of cardamom, produces 25,230 tons of dried cardamom capsules from 70,411 hectares, with Kerala accounting for nearly 90% of this production (Spices Board, 2025). Intensive cardamom cultivation in the Indian Cardamom Hills (ICH) with excessive usage of agrochemicals, with fewer varieties, and severe shade lopping leads to drastic changes in this agro-ecosystem, experiencing more abiotic and biotic stresses (Murugan et al., 2022; Nafeesa et al., 2024). Insect pest attacks are a major threat to small cardamom cultivation in India and more than sixty-nine species of insect pests are known to cause damage to cardamom (Williams and Watson, 1988, 1990; Gopakumar and Chandrasekar, 2002; Williams, 2004, 2005; Arif et al., 2009; Murugan et al., 2016; Joshi et al., 2023) with records of 22 species of scale insects throughout the world (Table I).

Formicococcus Takahashi, is a fairly large genus with 47 species worldwide, with a larger number of species in Oriental (33 species), Afrotropical (24 species), Palearctic region (22 species), and no distribution records in Nearctic and Neotropical regions. More species are known in China (15 species), followed by India (ten species). Of the 47 species of this genus, 27 species are likely to be monophagous; host plant records are not available for three species, but *F. lindingeri* (Bodenheimer) (25 species of 11 families), *F. njalensis* (Laing) (86 species of 33 families), *F. polysperes* Williams (34 species of 21 families), and *F. robustus* (Ezzat & McConnell) (27 species of 16 families) are polyphagous (García Morales et al., 2016). *Formicococcus njalensis* (Laing), *F. polysperes* Williams, and *F. robustus* (Ezzat & McConnell) have been intercepted repeatedly at the US ports of entry. In addition to these, *F. acerneus* Williams, *F. erythrinae* Williams, and *F. mangiferacola* Williams have also been reported some times from *Mangifera indica* L. imported from India to

the US (Miller et al., 2014). Surprisingly, *F. acerneus* has never been reported formally from India from the mango or other crops. This indicates that several species of this genus have quarantine importance and can spread if not addressed promptly.

This paper reports the occurrence of *Formicococcus polysperes* Williams (Hemiptera: Pseudococcidae) infesting small cardamom. It also aims to i) update distribution data and reflect therein the spread of its geographic range in India; ii) report new results gathered during documentation of host plants infested by *F. polysperes* from 1949 to 2025 by updating the list of host plants; iii) provide field and laboratory diagnostics as well as DNA sequences; and iv) find out causes of infestation on cardamom and its possible consequences and provide insight into possible management strategies.

Materials and methods

Survey and field observations. On discovery of a severe infestation of root mealybug at Ayyappankovil panchayat in the Idukki district, Kerala (9.9189° N, 77.1025° E) on a four-year-old cardamom plantation with variety 'Green gold' in the 3rd week of January 2025, the root zone portion of the infested plants was examined, and mealybug samples were collected with portions of cardamom roots for further studies. Field visits were made at fortnightly intervals from January 2025 to March 2025 to monitor the nature of the infestation. Samples were also collected from the nearby cardamom-growing areas by noting the visible symptoms of infestation for investigations on the occurrence of this pest, as well as to assess any variability in the pest species. The collected samples from different locations were preserved for the identification of the species. To assess the mealybug population and the nature of crop damage, the root zone portion of the cardamom plants was thoroughly examined with the help of an iron rake without causing much disturbance to the feeding roots. The mealybug population was recorded from thirty cardamom clumps, which were randomly selected in the study site. The number of mealybugs per 10 cm portion of the young roots from all four sides of the infested plant was noted. Symptoms of infestation were recorded on the roots as well as above-ground plant parts.

Processing and slide preparation. The terminologies used for the morphological structures of the adult female follow Williams & de Granara (1992). The mealybug species was diagnosed based on the keys by Williams (2004) and Williams and Watson (1988). Observations on the morphology of the mounted female were based on 84 specimens on twelve slides. Field photographs of the live mealybugs on plants were taken using a mobile camera, and photomicrographs of the live mealybugs were taken using a Leica DFC 420 camera mounted on a Leica M205A stereozoom microscope. Slide-mounted adult females were observed through a Nikon Eclipse 80i compound light microscope. All the insect specimens have been deposited in the National Insect Museum (NIM), ICAR-National Bureau of Agricultural Insect Resources, Bengaluru, Karnataka, India.

Host and geographical range documentation. For data collection on the geographic range and host plants of *F. polysperes* in India, slides deposited at the NIM, Bengaluru, were examined, along with a detailed review of published reports. These slides were prepared through our collection and the samples that were received for identification from different states. We have examined all the specimens depicted in Table I, except for those that were published in Williams (2004); however, data on the year of actual collection of the species, host

plant, and location were obtained from the collection data given in the same publication. The data is arranged in order of date and year of collection of the species to exactly interpret the sequence of events of its record. Many workers got the species identified from us, however did not document the new geographic distribution or new host records and hence this data is considered unpublished but has still been included in table II to trace the spread of the species with respect to geographic and host range.

Material examined. The data is arranged alphabetically according to the states of the country.

INDIA: Arunachal Pradesh: Pasighat, 28.0632° N, 95.3239° E, on *Colocasia esculenta* (L.) Schott (Araceae), 8 ♂♂, 20.xii.2022, Ajaykumara coll.

INDIA: Karnataka: Virajpet, Kodagu, 2.3056° N, 75.7545° E, on *Piper nigrum* L. (Piperaceae), 1 ♀, 14.i.2015, Chandish R. Ballal coll.; Koppa, Chikkamagaluru, 13.5327° N, 75.3558° E, on *Piper nigrum* L., (Piperaceae), 8 ♂♂, 15.xii.2017, Sawthi, N. Coll.; Balehonnur, Chikkamagaluru, 13.3490° N, 75.4651° E, on *Zingiber officinale* Roscoe (Zingiberaceae), 6 ♂♂, 19.xii.2017, Sawthi, N. Coll.; Halekote, Chikkamagaluru, 12.8479° N, 76.1871° E, on *Amorphophallus paeoniifolius* (Dennst.) Nicolson (Araceae), 8 ♂♂, 19.xii.2017, Sawthi, N. Coll.; Gonikoppa, Kodagu, 12.1843° N, 75.9263° E, on *Physalis minima* L. (Solanaceae), 10 ♂♂, 19.xii.2017, Sawthi, N. Coll.; Somvarpet, Kodagu, 12.5943° N, 75.8505° E, on *Phyllanthus niruri* L. (Phyllanthaceae), 5 ♂♂, 19.xii.2017, Sawthi, N. Coll.; Sakaleshpura, Hassan, 12.9442° N, 75.7866° E, on *Ageratum conyzoides* L. (Asteraceae), 8 ♂♂, 15.i.2018, Sawthi, N. Coll.; Virajpete, Kodagu, 12.1950° N, 75.8040° E, on *Synedrella nodiflora* (L.) Gaertn. (Asteraceae), 9 ♂♂, 08.ii.2018, Sawthi, N. Coll.; Virajpete, Kodagu, 12.1950° N, 75.8040° E, on *Erythrina subumbrans* (Hassk.) Merr. (Fabaceae), 3 ♂♂, 08.02.2018, Swathi, N. Coll.; Kodagu, 12.1950° N, 75.8040° E, on *Artocarpus heterophyllus* Lam. (Moraceae), 4 ♂♂, 08.02.2018, Swathi, N. Coll.; Kodagu, 12.1950° N, 75.8040° E, on *Gliricidia sepium* (Jacq.) Steud. (Fabaceae), 6 ♂♂, 08.02.2018, Swathi, N. Coll.; Kodagu, 12.1950° N, 75.8040° E, on *Grevillea robusta* A. Cunn. ex R.Br. (Proteaceae), 3 ♂♂, 08.02.2018, Swathi, N. Coll.; Kodagu, 12.1950° N, 75.8040° E, on *Areca catechu* L. (Arecaceae), 5 ♂♂, 08.02.2018, Swathi, N. Coll.; Mudigere, Chikkamagaluru, 13.1365° N, 75.6403° E, on *Piper nigrum* L. (Piperaceae), 4 ♂♂, 26.iii.2021, Kavya Yadav coll.; Hukkunda, Chikkamagaluru, 13.3121° N, 75.7284° E, on *Piper nigrum* L. (Piperaceae), 4 ♂♂, 12.iv.2021, Kavya Yadav coll.

INDIA: Kerala: Mullanakolly, Wayanad, 11.8176° N, 76.1639° E, 35 ♂♂ on *Piper nigrum* L. (Piperaceae), 17.xii.2013, Najitha Ummer coll.; Mullenakolly, Wayanad, 11.8176° N, 76.1639° E, 3 ♂♂ on *Piper nigrum* L. (Piperaceae), 12.i.2014, Najitha Ummer coll.; Mullenakolly, Wayanad, 11.8176° N, 76.1639° E, 2 ♂♂, on *Zingiber officinale* Roscoe (Zingiberaceae), 21.vi.2014, Najitha Ummer coll; Mullenakolly, Wayanad, 11.8176° N, 76.1639° E, 3 ♂♂ on *Amorphophallus paeoniifolius* (Dennst.) Nicolson, 21.vi.2014, Najitha Ummer coll.; Mullenakolly, Wayanad, 11.8176° N, 76.1639° E, 2 ♂♂, on *Ageratum conyzoides* L. (Asteraceae), 30.vi.2014, Najitha Ummer coll.; Mullenakolly, Wayanad, 11.8176° N, 76.1639° E, 4 ♂♂on *Synedrella nodiflora* (L.) Gaertn. (Asteraceae), 01.i.2015, Najitha Ummer coll.; Mullenakolly, Wayanad, 11.8176° N, 76.1639° E, 3 ♂♂on *Rhynchospora colorata* (Hitchcock) H. Pfeiff. (Cyperaceae), 01.i.2015, Najitha Ummer coll.; Mullenakolly, Wayanad, 11.8176° N, 76.1639° E, on *Erythrina* sp. (Fabaceae), 2 ♂♂, 01.i.2015, Najitha Ummer coll.; Mullenakolly, Wayanad, 11.8176° N, 76.1639° E, on *Clerodendrum infortunatum* L. (Lamiaceae), 2 ♂♂, 10.iii.2015, Najitha Ummer coll.; Mullenakolly, Wayanad, 11.8176° N, 76.1639° E, on *Phyllanthus niruri* L. (Phyllanthaceae), 5 ♂♂, 10.iii.2015, Najitha Ummer coll.; Mullenakolly, Wayanad, 11.8176° N, 76.1639° E, on

Physalis minima L. (Solanaceae), 3 ♀♀, 10.iii.2015, Najitha Ummer coll.; Mullenakolly, Wayanad, 11.8176° N, 76.1639° E, on *Urtica parviflora* Roxb. (Urticaceae), 2 ♀♀, 10.iii.2015, Najitha Ummer coll.; Vellanikkara, Thrissur, 10.5452° N, 76.2740° E, on *Macaranga peltata* (Roxb.) Müll.Arg. (Euphorbiaceae), 8 ♀♀, 08.ii.2017, Mani Chellappan coll.; Periye, Kasargod, 12.4076° N, 75.0932° E, on *Piper nigrum* L. (Piperaceae), 19 ♀♀, 27.vi.2019, Sachin G. Pai coll.; Chaturakinar, Kasargod, 12.2859° N, 75.1336° E, on *Musa acuminata* Colla (Musaceae), 8 ♀♀, 27.vi.2019, Sachin G. Pai coll; Padanakkad, 12.2598° N, 75.1130° E, on *Piper nigrum* L. (Piperaceae), 16 ♀♀, 21.ix.2019, Vidya, C. V. coll.; Kenichera, Wayanad, 11.7251° N, 76.1494° E, on *Persea americana* Mill. (Lauraceae), 5 ♀♀, 17.i.2020, Sachin G. Pai coll.; Kambalakkad, Wayanad, 11.6756° N, 76.0755° E, on *Ageratum conyzoides* L. (Asteraceae), 5 ♀♀, 15.ix.2020, Sachin G. Pai coll.; Paliyode, Thiruvananthapuram, 8.4288° N, 77.1497° E, on *Piper nigrum* L. (Piperaceae), 7 ♀♀, 19.vii.2023, Reji Rani coll.; Ayyappankovil, 9.6900° N, 77.0447° E, on *Elettaria cardamomum* (L.) Maton (Zingiberaceae), 7 ♀♀, 24.i.2025, Nafeesa, M. Coll.; Pampadumpara, 9.7967° N, 77.1586° E, on *Elettaria cardamomum* (L.) Maton (Zingiberaceae), 8 ♀♀, 24.i.2025, Nafeesa, M. Coll.; Vandanmedu, 9.7296° N, 77.1543° E, on *Elettaria cardamomum* (L.) Maton (Zingiberaceae), 9 ♀♀, 25.ii.2025, Nafeesa, M. Coll.; Nedumkandam, 9.8363° N, 77.1571° E, on *Elettaria cardamomum* (L.) Maton (Zingiberaceae), 8 ♀♀, 25.ii.2025, Nafeesa, M. Coll.

INDIA: Meghalaya: Umiam, 25.6649° N, 91.9029° E, on *Zingiber officinale* Roscoe (Zingiberaceae), 2 ♀♀, 30.xi.2013, Firake, D. M. coll; Umiam, 25.6649° N, 91.9029° E, on *Curcuma longa* L. (Zingiberaceae), 11 ♀♀, 24.iii.2016, Firake, D. M. coll; Umiam, 25.6649° N, 91.9029° E, on *Colocasia esculenta* (L.) Schott (Araceae), 2 ♀♀, 06.ii.2019, Firake, D.M. coll.

INDIA: Nagaland: Hekheshe, Medziphema, 25.7594° N, 93.8816° E, on *Colocasia esculenta* (L.) Schott (Araceae), 6 ♀♀, 02.04.2018, Jaydeep Halder coll.

INDIA: Tamil Nadu: Chidambaram, 11.4070° N, 79.6912° E, on *Mangifera indica* L. (Anacardiaceae), 1 ♀♀, 04.vii.2018, Ayyam Perumal coll.

DNA isolation, PCR amplification, and sequencing. The 90% ethanol-preserved mealybug specimens were kept at -20° C and the insect sample was washed two to three in distilled water to remove mealy matter. Genomic DNA was isolated from single mealybug by using QIAGEN DNeasy Blood and Tissue kit", Germany following the manufacturer's protocols. The remaining mealybug samples were kept as voucher specimens at -20°C. The DNA extracted was subjected for PCR amplification using BioRad C1000 Thermal Cycler. The PCR Product was amplified in 25 µl reactions (PCR Master mix 12.5 µl, forward and reverse primers 1 µl each, Template 3 µl and nuclease free water 7.5 µl). The amplified products were analyzed on 1.2% agarose gel electrophoresis and were sequenced at M/s Eurofins Pvt. Ltd, Bengaluru, India. The quality sequences were assembled with BioEdit 7.2 version then checked for homology, insertions and deletions, stop codons, and frame shifts by using NCBI-BLAST and deposited in NCBI GenBank database. Thermo-cycling parameters used for 28s rRNA gene are as follows.

28S large subunit ribosomal RNA gene (28S rRNA): The 28s D2-D3 ribosomal DNA region primers were 28sF: 5'-GCG AAC AAG TAC CGT GAG GG-3'and 28sR: 5'-TAG TTC ACC ATC TTT CGG GTCCC-3' (Whiting et al., 1997). Thermo-cycling parameters used for 28s D2-D3 consisted of an initial denaturation of 95ºC for 5 min,

followed by 35 cycles of denaturation at 95ºC (45 seconds), optimal annealing at 62.5ºC for 1 min, extension at 72 ºC for 1 min and final extension at 72ºC for 10 min, respectively.

The vouchers of the specimens subjected for molecular studies have also been deposited in the NIM, Bengaluru, India.

Results and discussion

Scale insects (Hemiptera: Coccoidea) infesting cardamom in the world. Based on the literature survey (Table I), 24 species of scale insects are known to infest cardamom in the world: nine each of armoured scale insects and mealybugs, four soft scale insects, and one each of rhizoecids and monophlebids. These have been reported from India (15 species), Papua New Guinea (6 species), and one species each from Western Samoa, Sri Lanka, and Pakistan. In India, 15 species cause damage, of which seven species were identified only up to the genus level. The maximum number of species are known from India; obviously there was a chance of coevolution because the crop is native to the country with several years of cultivation records. (García Morales et al., 2016).

Survey and field observations on cardamom root mealybug. The survey conducted at major cardamom growing areas (Ayyappankovil, Pampadumpara, Vandanmedu, and Nedumkandam) in the Idukki district indicated that the surveyed plantations with maintained shade of less than 40% showed symptoms of infestation. Both nymphs and adults of *F. polysperes* were aggregated on the cardamom roots; mostly the tender and white-colored roots were targeted by the pest (Figs. 1A & B). Upon infestation, the roots became shrunken and distorted (Fig. 1C); the color of the roots changed from cream white to dull brown, which later decayed (Fig. 1D). The average number of mealybugs per 10 cm portion of the young roots was recorded as 10.06 ± 0.83. In the above-ground portion, leaves showed yellowing and complete drying in the later stage. The infected cardamom clumps exhibited a sick appearance characterized by fewer, shorter tillers and unhealthy panicles (Figs. 1E & F).

Intensive farming in the Indian Cardamom Hills (ICH) resulted in higher accumulation of plant nutrients in tissues and organs, which made cardamom shoots more susceptible to insect pests and diseases (Murugan et al., 2017). Unlike other related crops like ginger and turmeric (on which this species of mealybug is reported repeatedly), the cardamom agroecosystem is unique, and the plantations are extensive and vast; they are interconnected in the entire growing area. This could pose more of a threat by the easy and quick spread of the pest in the future across the entire ICH.

A severe dilution of genetic diversity in terms of varietal diversification is evident in the Cardamom Hill Reserves (CHR) agroecosystem, Kerala (Murugan et al., 2022; Nafeesa et al., 2024). The *F. polysperes* infestation was noticed on the ruling variety ‘Green Gold’, which covers at least 80% of the cardamom area in the CHR agroecosystem. Shade lopping also has a severe impact on the microclimatic variation of the cardamom agroecosystem, which often increases pests like whiteflies, thrips, and root grubs (Prabhakaran Nair, 2006). Recently, a drastic change was noticed in the macro- and microclimatic factors, especially surface air temperature, precipitation pattern, and air humidity in the CHR system (Ramalingam et al., 2024).

These variations may be the reasons for the establishment and spread of this pest on cardamom roots and the expression of the symptoms in this unique system.

Identification and diagnostic characters of the mealybug infesting cardamom. Examination of thirty-five specimens mounted on five slides indicated the mealybug infesting cardamom roots was *Formicococcus polysperes* Williams. The field and mounted character of the mealybug are as follows.

Field characters (Fig. 1G) – Body of the female oblong to oval. Female becomes round with age, strongly convex above and very flat ventrally, coated dorsally with very fine, dense white powdery wax. Colour brownish yellow while appendages were transparent brown. Head and thorax smooth with visible abdominal intersegmental lines. Lateral wax filaments thick and short, surrounding body margin with longer filaments on abdomen and shorter on thorax and head.

Mounted female characters (Fig. 2) – Body of the mounted adult female broadly oval to circular, and membranous (Fig. 2A). Anal lobes well developed (Fig. 2B), ventral surface of each lobe with stout apical seta, bar seta, situated close to apical seta, and well-developed anal lobe bar (Fig. 2C). Dorsal surface of anal lobe with sclerotized derm (Fig. 2D). Antennae with 7 or 8 segments (Fig. 2E). Legs well developed. Translucent pores present on anterior and posterior surfaces of hind coxa (Fig. 2F) and on posterior surface of hind tibia (Fig. 2G). Circulus (Fig. 2H) divided by intersegmental line. Both anterior and posterior ostioles prominent (Fig. 2I & J), with inner edges of lips sclerotized, each lip bearing a few short setae and trilocular pores. Anal ring, situated at apex or slightly moved to dorsal surface of abdomen (Fig. 2K), normally bearing six setae (Fig. 2L). Cerarii numbering 18 pairs. Anal lobe cerarii (Fig. 2M) each containing 4–7 conical setae, differing slightly in size, and a small concentration of trilocular pores, all situated on a membranous area. Cerarii on abdominal segments V-VII each with 2 main conical setae and a few smaller conical setae distributed along margin in a concentration of trilocular pores (Fig. 2N & O). Cerarii on head, thorax and anterior abdominal segments each usually bearing 2 main conical seate, sometimes with 1 or more smaller conical setae anterior and posterior to main conical setae; ocular cerarii (C3) often with 3 or 4 conical setae (Fig. 2P).

Dorsal surface with numerous stout, stiff setae present (Fig. 2Q), many setae almost conical, some lanceolate, thicker at base than a trilocular pore; other setae slenderer; many setae with 1–3 trilocular pores next to setal collars. Most of the setae anterior to abdominal segment VIII short and thick; bases of setae as wide as trilocular pore.

Ventral surface with normal flagellate setae present (Fig. 2R); a few short setae, similar to dorsal setae, present around margins. Cisanal and obanal setae present. Multilocular disc pores (Fig. 2S) present posterior to vulva and in medial areas of posterior edges of abdominal segments IV-VII, often in single rows but sometimes in double rows. Trilocular pores (Fig. 2T) evenly distributed, less numerous than those on dorsum. Oral collar tubular ducts of 2 main sizes present (Fig. 2U); a large type, each a little wider than a trilocular pore, present in marginal groups on abdominal segments I-VII and in a conspicuous group lateral to each first coxa, rarely occurring on head between antennal bases. Ventral oral collar tubular ducts present in conspicuous group opposite to each anterior coxa (Fig. 2V).

Host and geographical range documentation of F. polysperes in India. This species was first collected from India, infesting *Arachis hypogaea* L. in the northeastern Indian peninsula (Odisha) and then was found in northeastern hilly regions (Meghalaya and Nagaland), north-central (Uttar Pradesh), eastern (West Bengal), central (Madhya Pradesh), southwestern (Karnataka), and the southwest corner (Kerala) of India (Table II). A total of 279 specimens on 64 slides were examined. Of these, there were 34 slides with 166 specimens from Kerala, 23 slides with 83 specimens from Karnataka, and 4 slides with 15 specimens from Meghalaya. From the remaining states, there were fewer than 10 specimens.

There were 25 species of host plants belonging to 23 genera and 17 families. Only the genus *Piper* had two species, *P. nigrum* and *P. betle*; the rest of the genera had only one species. In the collection, the frequency of occurrence of the host plants belonging to the family Piperaceae was highest (12), followed by Zingiberaceae (6) and Araceae (6). Since its first report, the pest is being reported on several economically important agricultural and horticultural host plants such as groundnut, taro, elephant foot yam, pepper, ginger, turmeric, arecanut, mango, banana, jackfruit, and avocado (Table II). It was reported in the northeast hilly region on ginger, turmeric and taro when grown as a sole crop (Firake et al., 2015; Firake et al., 2018; Halder et al., 2020), but was found to infest ginger and elephant foot yam when intercropped with pepper (Najitha, 2016). It was also reported on *Erythrina* sp., which is commonly used for trailing pepper vines, and eight weeds, belonging to seven families, which were found near infested pepper vines (Najitha, 2016). Swathi (2018) recorded the same weeds as hosts but, in addition to *Erythrina*, reported four more species of pepper standards that are infested by *F. polysperes*. All the above instances make it clear that for infestation and survival on several plant families, it was essential for the plants to be in close vicinity of the main infested host, which perhaps helped crawlers to move within soil to infest roots of different hosts. Ants such as *Crematogaster rogenhoferi* Mayr, *Lophomyrmex quadrispinosus* (Jerdon), *Paratrechina* sp. (Najitha, 2016); *Paratrechina longicornis* (Latreille), two species of *Plagiolepis*, a species of *Aphaenogaster* (Swathi, 2018); and *Monomorium* sp. (Yadav et al., 2025) have been reported from Kerala and Karnataka, tending *F. polysperes* on different hosts, possibly assisting movement of crawlers below soil. Only one natural enemy, viz., *Horniolus sororius* Poorani (Coleoptera: Coccinellidae), has so far been reported to be associated with *F. polysperes* feeding on pepper in Kerala (Vidya and Bhaskar, 2017). The presence of ants and difficulties in reaching the infestation inside the soil may be the reasons for fewer reports of natural enemies. The cumulative effect of these factors may help in rapid built up and spread of this pest, particularly in unique agroecosystems like spices.

It is clear from Table II that though *F. polysperes* was collected in India more than 75 years back, all the specimens collected from 1949 to 1992 were identified only in 2004. The next documented collection was only in 2013, but after that, this species has been collected and identified regularly to date. The species was collected from 10 states of India, but repeatedly only in southern states (Kerala and Karnataka), where pepper is grown extensively, and northeastern parts (Meghalaya, Arunachal Pradesh, and Nagaland), where ginger and turmeric are grown commonly (Table II). States like Mizoram, Sikkim, Assam, and Gujarat grow a lot of ginger, and Maharashtra, Andhra Pradesh, Telangana, and Gujarat are important states that grow turmeric. However, the pest was not able to be found on these crops in these areas. The species was collected repeatedly on similar hosts and from the same geographical areas. It is difficult to attribute any substantiated explanations for several time lags in the collection from 1949 to 1992 and the largest lull from

1992 to 2013. The hypogaeic nature of the habitat of the mealybug may be one of the reasons for its going unnoticed in spite of its presence for several years. Despite its likely record and collection, the collected samples might have remained unidentified due to the lack of taxonomic expertise in the group in the country, funds for shipping the specimens to renowned museums, and the lack of gratis identification facilities abroad. Furthermore, for any insect to get noticed and receive attention, it should colonize on economically important hosts, or there should be detailed faunal studies on the group encompassing large geographic areas.

DNA isolation and identification

The results of edited sequences matched with *Formicococcus polysperes* in the NCBI database for 28S rRNA with 96 to 97% similarity. After submission to NCBI, these nucleotide sequences were allotted different nucleotide accession numbers for 28S rRNA gene (PV768219, PV768220 and PV768221). Earlier to this molecular study, the accession numbers for ITS 2 (MZ920113) and COX I (MW025240, MW025198) have been allotted by NCBI for this species (Pai 2020; Kavya Yadav, 2022). Morphologically also, these specimens were identified in our laboratory.

Eco-friendly management attempts of F. polysperes infesting cardamom. Field demonstrations (Fig. 1H), involving soil drenching of *Lecanicillium lecanii* dust formulation (10^8 CFU/ml) at the rate of 20 grams per liter, found effective in reducing the mealybug population in the cardamom root zone. Freshly prepared solution of *L. lecanii* was applied in the root zone (5 liters per plant) twice at an interval of one month. Population reduction was noticed in the treated area compared to the untreated area two months after the initial application. Evaluation of other eco-friendly methods is underway.

Conclusion

Formicococcus polysperes is a polyphagous root-infesting mealybug, affecting 34 plant species across 21 families, and is commonly intercepted at US ports-of-entry on commodities imported from the Philippines (*Zingiber*), Thailand (*Zingiber*), and Vietnam (*Lansium*) (Miller et al., 2014). Only when damage symptoms occur on aerial plant parts can the presence of this species be identified. Often, an infestation begins with the purchase of infested plant material. In soil with sufficient moisture, young root mealybugs or crawlers are active. They can travel a short distance to reach the surrounding plants. They might use drainage holes to crawl from one seedling bag to another in the nurseries and more easily through irrigation water. Additionally, ants are responsible for spreading root mealybugs (Smitha et al., 2005). But associations of ants were not noticed in the cardamom agroecosystem along with *F. polysperes*. Unfortunately, very few natural enemies have been reported for this species, perhaps due to its subterranean habitat. The polyphagous nature of this mealybug species, revealed through this study, necessitates early and accurate identification of the species in recently affected areas. The colour photographs of the different life stages of the pest, as well as the aboveground and underground symptoms provided here, will help farmers and extension officers to detect new infestations of this species. Similarly, the slide-mounted characters, identification key to the Indian species of genus *Formicococcus* Takahashi published earlier (Joshi et al., 2020), and nucleotide sequences deposited through this study, will help researchers and students to separate this species from other common species of *Formicococcus*, leading to the development of accurate strategies for its containment. The

present article also emphasizes the necessity of studies on bioecology involving the interaction of biotic and abiotic factors, records of natural enemies, evaluation of eco-friendly methods, and possibilities for mass multiplication of effective bio-agents to improve the access of the farmers in the event of an outbreak of *F. polysperes*. The necessity of faunal studies on scale insect pest species, the availability of taxonomists working on the group, and free identification services are also highlighted in this paper.

Declarations

Author Contribution

SJ: Collection of mealybug species from different locations, slide mounting and determination of species, conceptualisation of the studyNM: Collection of mealybug infesting cardamom, Field observation on cardamom root mealybugMM: Field data interpretation (on cardamom mealybug)CMK: Molecular studiesGAKY: Collection of mealybugs from some host plants from Karnataka, Partial processing and determination, Molecular studiesKMA: Collection of mealybugs from the northeast hilly regionMC: Collection of mealybugs from some new host plants from Kerala

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Tables

Table I. Scale insects infesting *Elettaria cardamomum* in the world

Sl. No.	Scale insect species	Family	Country of record	Reference
1	Aonidiella inornata McKenzie	Diaspididae	Papua New Guinea	Williams and Watson, 1988
2	Hemiberlesia cyanophylli (Signoret)		Papua New Guinea	Williams and Watson, 1988
3	Hemiberlesia palmae (Cockerell)		Papua New Guinea	Williams and Watson, 1988
4	Aulacaspis sp.		India	Gopalkumar and Chandrasekar, 2002
5	Diaspis sp.		India	Gopalkumar and Chandrasekar, 2002
6	Aspidiotus destructor Signoret		India	Murugan et al., 2016
7	Aonidiella sp.		India	Murugan et al., 2016
8	Lepidosaphes sp.		India	Murugan et al., 2016
9	Aulacaspis elettaria Joshi & Nafeesa		India	Joshi et al., 2023
10	Planococcus minor (Maskell)	Pseudococcidae	Western Samoa	Williams and Watson, 1988
11	Planococcus citri		India	Gopalkumar and Chandrasekar, 2002
12	Dysmicoccus debregeasiae (Green)		India	Williams, 2004
13	Dysmicoccus subterreus Williams		India	Williams, 2004
14	Paraputo chimbuensis Williams		Papua New Guinea	Williams, 2005
15	Phenacoccus solenopsis Tinsley		Pakistan	Arif et al., 2009
16	Planococcus sp.		India	Murugan et al., 2016
17	Pseudococcus sp.		India	Murugan et al., 2016
18	Formicococcus polysperes Williams		India	Present study
19	Pulvinaria psidii Maskell	Coccidae	Sri Lanka	Green, 1909; Ali, 1971
20	Eucalymnatus tessellatus (Signoret		Papua New Guinea	Williams and Watson, 1990
21	Saissetia coffeae (Walker)		India	Gopalkumar and

Sl. No.	Scale insect species	Family	Country of record	Reference
				Chandrasekar, 2002
22	Pulvinaria sp.		India	Murugan et al., 2016
23	Icerya samaraia (Morrison)	Monophlebidae	Papua New Guinea	Williams and Watson, 1990
24	Xenococcus annandalei	Rhizoecidae	India	Deepthy et al., 2017

Table II. Year of collection, host plants and distribution of *Formicococcus polysperes* Williams in India.

Year of collection	Host	Family	Location, State	No. of slides	Year of determination	Author and year of publication
1949	Arachis hypogaea L.	Fabaceae	Orissa	-	-	Williams, 2004
1978	Piper betle L.	Piperaceae	West Bengal	-	-	Williams, 2004
1984	Areca catechu L.	Arecaceae	Uttar Pradesh	-	-	Williams, 2004
1991	P. betle	Piperaceae	Uttar Pradesh	-	-	Williams, 2004
1991	Piper nigrum L.	Piperaceae	Kerala	-	-	Williams, 2004
1992	P. betle	Piperaceae	Madhya Pradesh	-	-	Williams, 2004
2013	P. nigrum	Piperaceae	Kerala	6	17.12.2013	Najitha, 2016
2013	Zingiber officinale Roscoe	Zingiberaceae	Meghalaya	1	30.11.2013	Firake et al., 2015
2014	P. nigrum	Piperaceae	Kerala	1	12.01.2014	Najitha, 2016
2014	Z. officinale	Zingiberaceae	Kerala	1	21.06.2014	Najitha, 2016
2014	Amorphophallus paeoniifolius (Dennst.) Nicolson	Araceae	Kerala	1	21.06.2014	Najitha, 2016
2014	Ageratum conyzoides L.	Asteraceae	Kerala	1	30.06.2014	Najitha, 2016
2015	Synedrella nodiflora (L.) Gaertn.	Asteraceae	Kerala	1	01.01.2015	Najitha, 2016
2015	Rhynchospora colorata (L.) H. Pfeiff.	Cyperaceae	Kerala	1	01.01.2015	Najitha, 2016
2015	Erythrina sp.	Fabaceae	Kerala	1	01.01.2015	Najitha, 2016
2015	P. nigrum	Piperaceae	Karnataka	1	14.01.2015	Chandish R. Ballal, Unpublished
2015	Clerodendrum	Lamiaceae	Kerala	1	10.03.2015	Najitha,

Year of collection	Host	Family	Location, State	No. of slides	Year of determination	Author and year of publication
	infortunatum L.					2016
2015	Phyllanthus niruri L.	Phyllanthaceae	Kerala	1	10.03.2015	Najitha, 2016
2015	Physalis minima L.	Solanaceae	Kerala	1	10.03.2015	Najitha, 2016
2015	Urtica parviflora Roxb.	Urticaceae	Kerala	1	10.03.2015	Najitha, 2016
2016	Curcuma longa L.	Zingiberaceae	Meghalaya	2	24.03.2016	Firake et al., 2018
2017	Macaranga peltata (Roxb.) Müll.Arg.	Euphorbiaceae	Kerala	1	08.02.2017	Mani Chellappan, Unpublished
2017	P. nigrum	Piperaceae	Karnataka	2	15.12.2017	Sawthi, 2018
2017	Z. officinale	Zingiberaceae	Karnataka	2	19.12.2017	Sawthi, 2018
2017	A. paeoniifolius	Araceae	Karnataka	3	19.12.2017	Sawthi, 2018
2017	P. minima	Solanaceae	Karnataka	3	19.12.2017	Swathi, 2018
2017	P. niruri	Phyllanthaceae	Karnataka	2	19.12.2017	Swathi, 2018
2017	A. conyzoides	Asteraceae	Karnataka	2	15.01.2018	Swathi, 2018
2017	S. nodiflora	Asteraceae	Karnataka	2	08.02.2018	Swathi, 2018
2017	Erythrina subumbrans (Hassk.) Merr.	Fabaceae	Karnataka	1	08.02.2018	Swathi, 2018
2017	Artocarpus heterophyllus Lam.	Moraceae	Karnataka	1	08.02.2018	Swathi, 2018
2017	Gliricidia sepium (Jacq.) Steud.	Fabaceae	Karnataka	1	08.02.2018	Swathi, 2018
2017	Grevillea robusta A.Cunn. ex R.Br.	Proteaceae	Karnataka	1	08.02.2018	Swathi, 2018

Year of collection	Host	Family	Location, State	No. of slides	Year of determination	Author and year of publication
2017	A. catechu	Arecaceae	Karnataka	1	08.02.2018	Swathi, 2018
2018	Mangifera indica L.	Anacardiaceae	Tamil Nadu	1	04.07.2018	Ayyam Perumal, Unpublished
2018	Colocasia esculenta (L.) Schott	Araceae	Nagaland	1	02.04.2018	Halder et al., 2020
2019	P. nigrum	Piperaceae	Kerala	5	27.06.2019	Pai, 2020
2019	Musa acuminata Colla	Musaceae	Kerala	2	27.06.2019	Pai, 2020
2019	C. esculenta	Araceae	Meghalaya	1	06.02.2019	Firake, Unpublished
2019	P. nigrum	Piperaceae	Kerala	2	21.09.2019	Vidya, C. V., Unpublished
2020	Persea americana Mill.	Lauraceae	Kerala	1	17.01.2020	Pai, 2020
2020	A. conyzoides	Asteraceae	Kerala	1	15.09.2020	Pai, 2020
2021	P. nigrum	Piperaceae	Karnataka	1	26.03.2021	Kavya Yadav, 2022
2021	P. nigrum	Piperaceae	Karnataka	1	12.04.2021	Kavya Yadav, 2022
2022	C. esculenta	Araceae	Arunachal Pradesh	1	20.12.2022	Ajay Kumara, Unpublished
2023	P. nigrum	Piperaceae	Kerala	1	19.07.2023	Reji Rani Unpublished
2025	Elettaria cardamomum (L.) Maton	Zingiberaceae	Kerala	2	24.01.2025	Present study
2025	E. cardamomum	Zingiberaceae	Kerala	2	25.02.2025	Present study

Figures

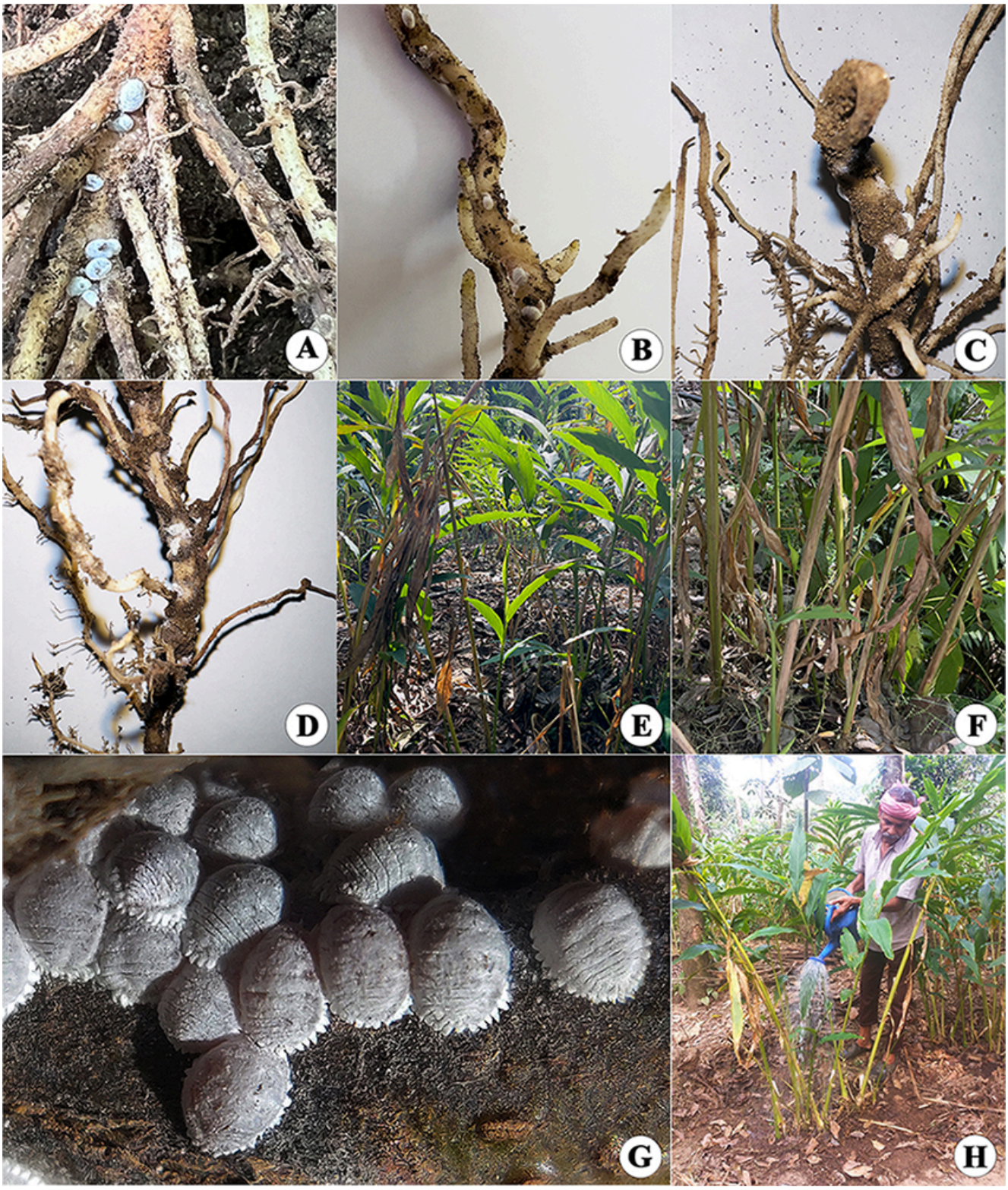

Figure 1

Formicococcus polysperes Williams (A & B) Mealybug infestation on the tender and white-coloured cardamom roots; (C) Distorted and shrunken roots; (D) Dull brown and decayed roots; (E & F) Infected cardamom clumps; (G) Photomicrograph of *F. polysperes* females; (H) Soil drenching with *Lecanicillium lecanii*

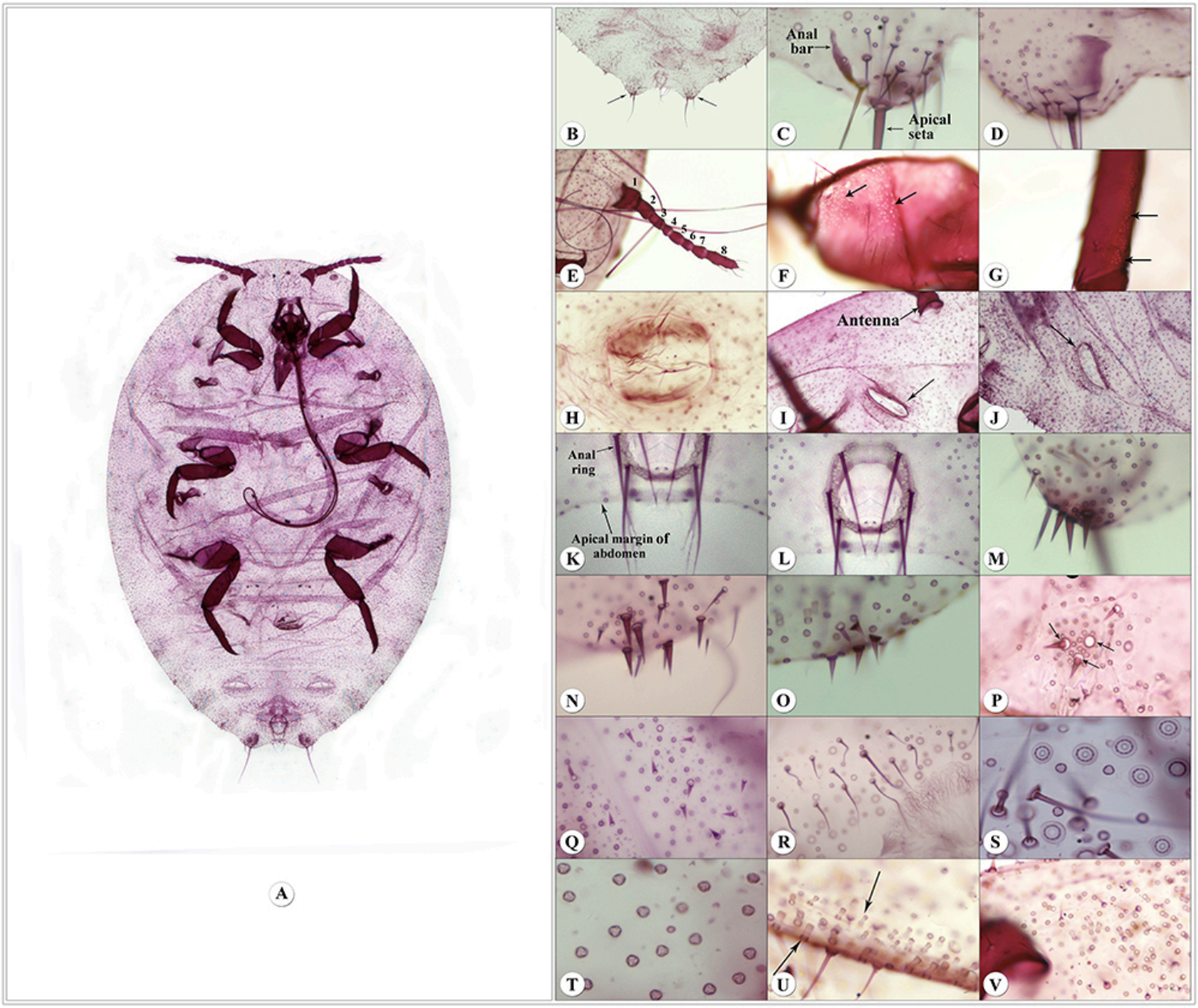

Figure 2

Diagnostic characters of *Formicococcus polysperes* Williams (A) Mounted female; (B) Well developed anal lobes; (C) Ventral side of anal lobe; (D) Dorsal side of anal lobe; (E) Antenna; (F) Translucent pores on hind coxa; (G) Translucent pores on tibia; (H) Circulus; (I) Anterior ostiole; (J) Posterior ostiole; (K) Location of anal ring on dorsum; (L) Anal ring setae; (M) Anal lobe cerarius; (N) Penultimate cerarius; (O) Anterior abdominal cerarius; (P) Ocular cerarius; (Q) Dorsal setae; (R) Ventral setae; (S) Multilocular disc pores; (T) Trilocular pores; (U) Oral collar tubular ducts; (V) Aggregation oral collar tubuar ducts opposite to anterior coxa