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continued on the back inside cover

Cover: Tamil Lacewing *Cethosia nietneri* with colour pencils and watercolours for the background; detailing with fine liners by Elakshi Mahika Molur.



Morphological characterization and ecological insights of *Pseudonapaeus* cf. *candelaris* (L. Pfeiffer, 1846) in the Pir Panjal Range of western Himalaya

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Abstract: *Pseudonapaeus* cf. *candelaris* is a terrestrial snail species belonging to the Enidae family, specifically inhabiting the Pir Panjal Range of the western Himalaya. This species displays a unique shell morphology with prominent features including deep furrows, a smooth outer surface, cylindrical form, gradually tapering apex, spiral bands and axial ribs. This study examines the morphometric characteristics of shell and distinct structural patterns observed in specimens from various sites within the region. By documenting these morphological attributes, the research enhances our taxonomic understanding of *P. cf. candelaris*, addressing aspects of its classification and ecological role. The findings present critical information for conservation efforts aimed at protecting this regionally significant, endemic snail species.

Keywords: Biodiversity, endemic, gastropods, high altitude, molluscs, shell morphology, snail, terrestrial.

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Competing interests: The authors declare no competing interests.

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Author contributions: HA led the entire field sampling, data collection and preparation of the manuscript. IA and Dr. NAA gave study conceptualization, design, manuscript review, editing and supervision. Their significant contributions were crucial for the improvement of the overall quality of the manuscript.

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INTRODUCTION

The family Enidae comprises a group of pulmonate gastropod molluscs that primarily inhabit terrestrial environments. Woodward (1903) was the first to describe these land snails and they are well known for their air breathing mechanism. Enidae, a taxonomic family belonging to the phylum Mollusca, exhibits notable diversification within this phylum, encompassing approximately 66 genera and 300 species (Molluscabase 2024). The family Enidae is native to India, comprises approximately 29 species. These species are classified into three genera: *Mirus* Albers, 1850 (consisting of five species), *Serina* Gredler, 1898 (consisting of five species), and *Pseudonapaeus* Westerlund, 1887 (consisting of 19 species). Among these species, 21 are found exclusively in India (Kobelt & Mollendorff 1903; Gude 1914; Ray 1951; Solem 1979; Ramakrishna et al. 2010; Tripathy et al. 2018). With the progress of technology, numerous taxa have undergone taxonomic redescrptions. The genus *Pupinidius* Moellendorff belongs to the family Enidae and has undergone comprehensive examination, resulting in the redescrptions of 14 out of the 16 known species and subspecies (Wu & Zheng 2009). In a study conducted by Alonso et al. (2006), it was reported that five previously unidentified species belonging to the family Enidae of land snails were identified from La Gomera, located in the Canary Islands. The findings of Wu & Wu (2009, 2013) improves the understanding about the characteristics of this family, which still needs to be clarified in terms of its subdivision or make-up of subgroups. The taxonomic classification of the family Enidae has undergone thorough scrutiny and revision throughout its history. It has also been reported that taxonomy of this species delineated several subfamilies, including Pseudonapaeinae, Chondrulopsininae, Merdigerinae, Buliminusinae, Andronakiinae, Retowskiinae, Eninae, and Multidentulini (Schileyko 1998). Furthermore, the following taxonomy by Bouchet et al. (2017) tried to simplify things by narrowing the classification down to two subfamilies: Eninae and Buliminusinae. Bank & Neubert (2016) made improvements to the existing classification system by dividing the Eninae into four distinct tribes, namely: Enini, Multidentulini, Merdigerinae, and Pseudonapaeini. In addition to taxonomic factors, Enidae snails have notable versatility in adapting to a wide range of terrestrial environments, including forests, grasslands, and cold deserts (Ozgo 2014; Zhukov et al. 2019). The presence of adaptation in this species is responsible for the intricate morphological and behavioural characteristics identified

within the taxonomic group. Additionally, their evolution of a functional lung distinguishes them from their aquatic relatives and allows them to thrive on land (Lodi & Koene 2016; Nandy et al. 2022). The family Enidae is a compelling illustration of evolutionary flexibility among gastropod molluscs, including around 20% of the overall population of land snails (Alonso et al. 2006).

The taxonomic classification of the genus *Pseudonapaeus*, as first proposed by Westerlund (1887), occupies a notable position within the Eninae subfamily of the Enidae. According to Tripathy et al. (2022), *Pseudonapaeus* encompasses 136 recognized species and exhibits a broad geographical distribution spanning central, southern, southeastern Asia, and Japan. The distribution of this genus in India is primarily limited to the western Himalaya, comprising 18 species (Ahmed et al. 2023). The taxonomic complexity surrounding this genus has played a significant role in advancing our knowledge of terrestrial gastropods. The taxonomy of *Pseudonapaeus* has faced difficulties, particularly in classification and species identification (Feruzza 2017). The complexities occur due to the varied physical traits of different species, posing challenges in accurately defining separate taxonomic groups. The taxonomic classification of this group includes multiple species, each of which poses distinct difficulties in accurate identification. The challenges arise from nuanced variations in shell form, coloration, and size, underscoring the importance for taxonomists to demonstrate meticulousness in discerning distinguishing characteristics. The *Pseudonapaeus* presents a captivating subject for scholarly investigation, providing valuable perspectives on the difficulties related to taxonomy, classification, and species identification within the Enidae family and the broader realm of terrestrial gastropods.

The Pir Panjal Range, a significant mountain range located in the northern section of the Indian subcontinent, has a crucial role in shaping the distribution patterns of the Enidae family and the genus *Pseudonapaeus* within the area. *Pseudonapaeus cf. candelaris*, a unique species of the genus *Pseudonapaeus*, demonstrates a significant distribution within the specified geographic area. The existing literature over the last two centuries emphasizes the difficulties encountered in taxonomy and the ever-evolving nature of scientific investigation. The progress in technology and methods has made it easier to learn more about *Pseudonapaeus cf. candelaris* and the Enidae family, which is an essential contribution to the field of malacology. The extensive body of literature on gastropod studies offers a significant basis for

present and future research, underscoring the enduring significance of investigating these land-dwelling molluscs within shifting scientific frameworks.

The scholarly discourse surrounding the distribution patterns and ecological preferences of the *Pseudonapaeus cf. candelaris* species in the western Himalaya has undergone significant development, owing to the outstanding contributions made by numerous workers. Hume Cuming, Esq. initially gathered the specimens, which were subsequently documented by Pfeiffer (1846). Pfeiffer's knowledge of the species' environment was limited, whereas Reeve asserted that it originated from regions including Europe and Asia (Reeve 1849). Specimens of the species were gathered by Thomas Thomson from Takht-i-Suleiman in Srinagar, India, during the exploration conducted in 1847–48 (Woodward 1856; Benson 1857). The occurrence of the species in the higher slopes of Kashmir was further investigated in subsequent research conducted by Hanley & Theobald (1876). Later on, Nevill (1878) expanded the geographical range of this family included Tandali from Himachal Pradesh, India. Theobald (1878) expanded upon the existing studies by investigating the elevated regions in Kashmir. Gude (1914) conducted an extensive study encompassing Fort Lockhart in Pakistan as a habitat for the subject under examination.

Conversely, Ramakrishna et al. (2010) identified Kashmir as the location of occurrence based on significant literature sources. Various geographical areas, such as Chandak from the Poonch District of the Pir Panjal Range in India (Ahmed et al. 2023), exemplify the inclusive scope of these investigations. The body of literature, which spans over a century, encompasses diverse research endeavours that have significantly enhanced our comprehension of the distribution and ecology of *Pseudonapaeus cf. candelaris* in the western Himalaya.

There is a significant knowledge deficit on the variety and ecological aspects of land molluscs, specifically *Pseudonapaeus cf. candelaris*, in the vicinity of the Takht-i-Suleiman type locality situated on the eastern flank of the Pir Panjal Range. Even with the proximity of the species, existing literature indicates a significant gap in detailed research about the ecology and diversity of land molluscs within this geographic region. Significantly, the research conducted by Ahmed et al. (2023) underscores the necessity for further investigation and the dearth of periodic evaluations of species by checklists. This study notably draws attention to the inadequate focus on terrestrial molluscs such as *Pseudonapaeus cf. candelaris* and their ecological

significance. The research holds great importance, mainly due to its proximity to the type locality. It presents a distinct chance to acquire knowledge regarding habitat preferences, population dynamics, and prospective conservation strategies for this species. In addition, the need for more consideration of the ecological aspects of land molluscs in the region gives rise to apprehensions regarding the potential ramifications for the agricultural sector at the local level. It is imperative to undertake a targeted research endeavour that examines the ecology of *Pseudonapaeus cf. candelaris* and other terrestrial molluscs in the Pir Panjal Range. Addressing this study would make a valuable contribution to the scientific comprehension of the species while also carrying practical consequences for promoting local agricultural sustainability and preserving biodiversity.

It is imperative to adopt a multidimensional approach to effectively address the research gap in precisely describing pupillid shell features. Using ultrastructure images of the shell surfaces gives us a high-resolution picture that lets us look at many different morphological features, like the structure of the sutures, the structure of the tips, and the structure of the shell openings. The utilization of this sophisticated imaging technology overcomes the constraints inherent in traditional microscopy methods. Integrating molecular identification techniques, particularly DNA barcoding, can enhance taxonomy classifications with additional precision. The primary objective of molecular analysis will be to investigate genetic markers, enhancing species identification's precision. Putting these methods together and linking morphological and molecular approaches creates a strong foundation for fully understanding the features of the pupillid shell. The comprehensive nature of this technique addresses the deficiency in morphological analysis and establishes a foundation for the following research endeavours, encompassing ecological investigations. The objective is to enhance our comprehension of these species, aiding in the evaluation of damage, development of conservation measures and implementation of management methods that are well-informed and grounded in a more comprehensive and precise understanding of pupillid land snails. The present study significantly enhances our comprehension of terrestrial snails' biodiversity and ecological processes within the demanding topographies of the Pir Panjal Range and the wider Himalayan region besides provide us significant opportunities for enhancing the understanding of the complex interplay between these gastropods and their alpine habitats.

MATERIAL AND METHODS

Field sampling

From April 2021 to March 2023, the specimens of *Pseudonapaeus cf. candelaris* were meticulously collected in the Rajouri and Poonch Districts of the Pir Panjal Range (Figure 1). Monthly surveys, following an active visual search strategy. Specimens underwent photographic documentation and precise shell measurements in the laboratory using a Leica M205 stereo microscope and Mitutoyo digital calliper. Identification was confirmed through morphological examination and comparison with type specimens. Preserved at the ATREE Biodiversity Laboratory, this research significantly enhances the understanding of terrestrial mollusc taxonomy in the region.

Morphological analysis

The collected individuals were morphologically examined for standard conchological characteristics such as shell shape, size, aperture shape, width, architecture on the shell, etc. The shell morphology was compared

with earlier descriptions (Pfeiffer 1846; Benson 1857). The photos of the syntype from the Natural History Museum London and other voucher specimens (ZMA. MOLL.34612 at Naturalis Biodiversity Center) were compared for identification.

RESULTS

Systematic position

Order: Gastropoda
 Subclass: Heterobranchia
 Order: Stylommatophora
 Family: Enidae B.B. Woodward, 1903 (1880)
 Subfamily: Eninae B.B. Woodward, 1903 (1880)
 Genus: *Pseudonapaeus* Westerlund, 1887
Pseudonapaeus cf. candelaris

Shell morphology

The shell of this sinistral gastropod exhibits a cylindrical morphology characterized by a sleek outer surface and faintly pigmented bands. On average, it is

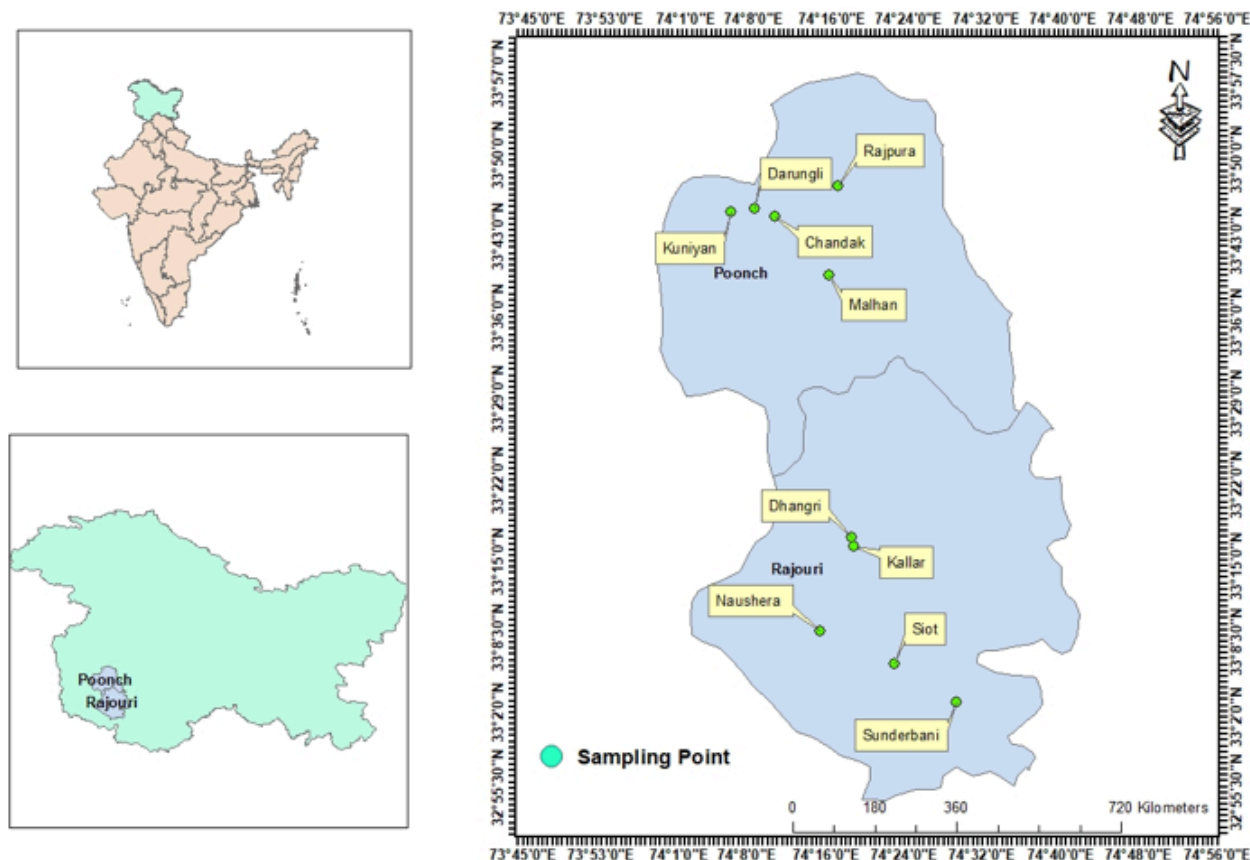


Figure 1. Map showing the sampling locations in Poonch and Rajouri Districts in Jammu & Kashmir (J&K), India. The inset maps show the location of the J&K, Poonch and Rajouri districts.

25.2 mm in length and has a diameter of 5.8 mm (Image 1). Deep grooves and a top that gradually narrows to a sharp point distinguish the shell. It displays slightly slanted stripes over an off-white base colour. The terminal one exhibits a series of nine flat bends, gradually decreasing in obliquity, culminating in a rounded base. The semioval aperture has an interior characteristic of bright white coloration. A peristome with enlarged white folds encircles the opening, harmoniously connecting them with a delicate callus along the borders. Significantly, the columellar region exhibits a pronounced dilation, contributing to the complexities inherent in the morphological characteristics of this snail shell. On examining the ultrastructure images of the shell (Image 1a), the surface is smooth with a slowly obliquely slight band without horizontal streaks, the groove is not too wide and the shell tip is concentrated bluntly without a sharp tip.

Ecological habitat

By methodically collecting 79 specimens, it was possible to ensure a complete representation of the species' range across various environments. A rigorous assessment was carried out to examine the species' ecological intricacies, focusing on its habits and environment. The study on *Pseudonapaeus cf. candelaris* in the Pir Panjal Range of the western Himalaya has provided a detailed understanding of species preferences for several environmental and habitat factors in the terrestrial ecosystem. The species exhibited a consistent

occurrence in environments defined by soils with good drainage, particularly red clay, located beneath a thick layer of fallen leaves and within regions with abundant vegetation that get limited direct sunlight (Image 2b). The altitude distribution of *P. cf. candelaris*, which spans from 900 to 1,500 m, has been identified as a crucial element that highlights its ability to adapt to specific elevational ranges within the Pir Panjal Range (Image 2a). The soil study indicated a pH range of 6.5–7.8, with a distinct inclination towards habitats with a substantial calcium content of 7.9–9.8 mg/g. This preference is particularly evident in locations that experience semi-arid climatic conditions. Observing dead specimens within the sandy mud and loamy soil indicates the possibility of these locations serving as potential hibernation places during high temperatures and aridity. Field observations showed a notable increase in specimen abundance from August to mid-September. This time frame accounted for approximately 75% of the studied population. The ecological study provides a complete overview of the essential climatic and ecological elements that play a crucial role in regulating the distribution patterns of *P. cf. candelaris*. These parameters, identified as critical determinants, include humidity, altitude, soil type, and temperature.



Image 1. The shell image of *Pseudonapaeus cf. candelaris* collected from the Pir Panjal area: a—during the present study | b—the syntype with catalogue number 20180423 from the Natural History Museum, London. Scale 1 cm. © Hilal Ahmed.

Table 1. Comparative morphological study of different morphologically similar land snails of the Enidae family distributed in northern India.

	Characters	<i>Pseudonapaeus purii</i>	<i>P. domina</i>	<i>P. arcuatus</i>	<i>P. vibex</i>	<i>Serina nevilleana</i>	<i>Pseudonapaeus cf. candelaris</i>
1	Shell shape and size	Cylindrical, 15 mm x 5.5 mm	Cylindrical, 23 mm x 9 mm	Variable, 12.5–21 mm x 5–8 mm	Cylindrical, 15.1 mm x 5.0 mm	Cylindrical, similar to <i>P. purii</i> , 11.8 x 4.3 mm	Cylindrical, elongated, 25.2 mm x 5.8 mm
2	Coloration	Chalky-white coating on last four whorls; original horny-brown on uppermost whorls	Shell with reddish-brown oblique stripes	Dark horny-yellow, faint white lines on body whorls	Dark horny-yellow, with characteristic hyaline white lines	Grayish-white to off-white, similar to <i>P. cf. candelaris</i>	Off-white with slightly slanted stripes; bright white aperture interior
3	Surface texture	Distinct longitudinal plications, corrugated similar to <i>Serina nevilleana</i>	Smooth, slight striations on outer surface	Smooth with faint transverse lines	Smooth with hyaline white lines	Smooth with faint grooves	Smooth with faintly pigmented bands; deep grooves; tip blunt without sharp point
4	Aperture	Oblong-ovate, pale brownish interior, edentate	Semi-oval, slightly oblique	Variable, 5 mm x 4 mm to 7.5 mm x 6 mm	Rounded, variable diameter	Semi-oval, similar to <i>P. cf. candelaris</i>	Semi-oval, bright white interior; peristome with thick white folds; distinct columellar dilation
5	Whorls	Four distinct whorls, last one with chalky-white coat	Five to six, with reddish-brown markings on final whorls	Five to six, smooth, regular in structure	Four to five, with hyaline lines	Five to six, faintly pigmented	Nine slightly oblique bends on final whorl, decreasing in obliquity towards the rounded base
6	Habitat	High-altitude mostly under leaf litter (>3,000 m)	Western Himalaya, deep clay soil	Swagni Maidan, sloping meadow (<3,000 m)	Chakrata and Deoban, high-altitudes (2,424–3,030 m)	High-altitude regions, semi-arid conditions	Well-drained red clay at altitudinal range 900–1,500 m
7	Endemism	Yes, rediscovered in 2018, Great Himalayan National Park	Yes, western Himalaya	Yes, found in lesser Himalayan region	Yes, prevalent in middle Himalayan region	Endemic to some Himalayan regions	Yes, widespread across western Himalaya
	References	Tripathy et al. 2022; Ray 1951	Benson 1857; Gude 1914	Reeve 1849; Gude 1914; Rensch 1955	Rensch 1955; Gude 1914	Theobald 1881; Gude 1914	Present study

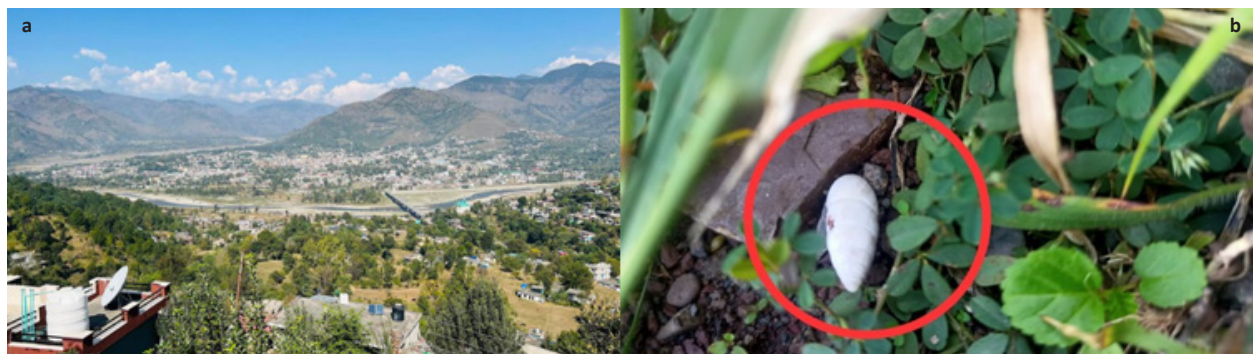


Image 2. a—The typical habitat of *Pseudonapaeus cf. candelaris* in the Pir Panjal region of Jammu & Kashmir | b—the microhabitat with a living individual. © Hilal Ahmed.

DISCUSSION

The rediscovery of *Pseudonapaeus cf. candelaris*, a species belonging to the Enidae family and native to the Pir Panjal Range in the western Himalaya, represents a significant achievement in malacological research. This species has been challenging to find since it was

documented 170 years ago at Takht-i-Suleiman in Srinagar, Kashmir (Woodward 1856). Many scholars from different periods have been interested in studying this species, including Reeve (1849), Woodward (1856), Hanley & Theobald (1876), Nevill (1878), Theobald (1878), Gude (1914), Ramakrishna et al. (2010), and Tripathy et al. (2018). Old records do not always have

solid proof; they often rely on lists or collections of historical writings (Gude 1914; Ramakrishna et al. 2010; Tripathy et al. 2018) that do not give essential details like reference numbers and pictures, or drawings that are needed to confirm the specimens that were reported. Reeve's (1849) early claim that the species was limited to Asia and Europe, which was later withdrawn, introduces a level of intricacy to the historical account. The problem worsens because specimens still need to be correctly identified as *Zootecus* sp. even though they have apparent physical features that make them easy to spot. The persistent uncertainty and lack of modern reports highlight the rarity of *P. cf. candelaris* in the Pir Panjal Range, as emphasized in recent studies (Ahmed et al. 2023). The clear connection of the species with its original location in Kashmir is an undeniable aspect of its importance, both in the past and present.

The shells of *Pseudonapaeus cf. candelaris* in the Pir Panjal range exhibit unique traits specific to the species. Typically, these shells have a cylindrical shape with a pointed tip that resembles a candle. The oval-shaped aperture and the spire height, which is around half of the shell's overall height, are distinctive characteristics of the species. Certain shells exhibit chromatic differences and development lines, indicating the possibility of variety within the population. *P. cf. candelaris* can be distinguished from similar species like *P. domina* and *P. arctuatus* based on its distinctive physical characteristics (Table 1). These include a sinistral shell, a smooth surface, a thick aperture shell without horizontal streaks and 3–4 middle whorls that are almost the same width. According to historical records by Nevill (1878) and Theobald (1878), many sinistral shells were recorded, while dextral shells were less commonly seen. The lack of visual evidence and preserved specimens in historical literature raises doubts about the occurrence of dextral shells. This scepticism is particularly relevant considering the extensive surveys conducted by multiple expeditions and authors over the past two years (Ahmed et al. 2023). Theobald (1878) also talks about how the sinistral and dextral shells are very different in size and suggests that the dextral shells might be *Pseudonapaeus domina* with close-type locations. Discernible distinguishing characteristics have yet to be found between the two.

This study provides a comprehensive analysis of shell morphology for *Pseudonapaeus cf. candelaris* in the Pir Panjal range of the northwestern Himalaya. In addition, it includes a succinct ecological investigation specific to this species. By combining traditional taxonomic methods with ecological assessment, the understanding of this mollusc species is significantly improved in this

ecologically crucial region. Future research should prioritize an in-depth exploration of the ecological implications of *P. cf. candelaris* and its role within the Pir Panjal ecosystem.

This research underscores the need for extensive biodiversity studies in the western Himalayas, inspired by the rediscovery of *P. cf. candelaris*—a species initially documented by scientists over 170 years ago during several expeditions. This rediscovery emphasizes the pressing need to investigate and preserve the region's rich biodiversity.

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Articles

Culture and provisioning: the case of Human-Long-tailed Macaque *Macaca fascicularis* (Raffles, 1821) interactions in Sumile, Butuan City, Philippines

– Fritche H. Lapore, Debbie S. Aseñas & Sherryl L. Paz, Pp. 26443–26458

Noteworthy comments on birds for mega-diverse Myanmar

– Swen C. Renner, Saw Moses, Lay Win, Thein Aung, Myint Kyaw, Saw Myat Ohnmar, Thiri Dae We Aung, Kay Thwe Myint, Sai Sein Lin Oo, Paul J.J. Bates & Marcela Suarez-Rubio, Pp. 26459–26467

Ultra-structure of antenna, eye, mouthparts and sensilla of *Cheilomenes sexmaculata* Fabricius, 1781 (Coccinellidae: Coleoptera)

– Prakash Ghagargunde & Mandar S. Paingankar, Pp. 26468–26478

Morphological characterization and ecological insights of *Pseudonapaeus cf. candelaris* (L. Pfeiffer, 1846) in the Pir Panjal Range of western Himalaya

– Hilal Ahmed, Imtiaz Ahmed & N.A. Aravind, Pp. 26479–26486

Communications

Diet and nutrient balance of wild Asian Elephants *Elephas maximus* in Nepal

– Raj Kumar Koirala & Sean C.P. Coogan, Pp. 26487–26493

Avian diversity in wetlands of southwestern Kerala of India during COVID

– Vijayakumari Sudhakaran Bindu & S. Sajitha, Pp. 26494–26503

Checklist on the ichthyofaunal resources and conservation status of Dikhu River, Nagaland, India

– Metevinu Kechu & Pranay Punj Pankaj, Pp. 26504–26514

A study on the diversity of butterflies in selected landscapes of the Indian Institute of Technology, Guwahati campus, Assam, India

– Uma Dutta, Sonali Dey & Deepshikha Moran, Pp. 26515–26529

Sphaeroma taborans sp. nov., a new species of wood-boring isopod (Crustacea: Isopoda: Sphaeromatidae) from Munroe Island, Ashtamudi Estuary, Kerala, India

– M.S. Arya, A. Biju & Dani Benchamin, P. 26530–26537

A report on Conidae (Gastropoda) from the Karnataka coast – distribution and shell morphometry

– B.S. Chandan, R. Shyama Prasad Rao & Mohammed S. Mustak, Pp. 26538–26546

New distribution record and DNA barcoding of the steno-endemic plant *Cordia diffusa* (Boraginaceae)

– M. Haritha, D. Leena Lavanya & H. Abinaya, Pp. 26547–26552

Short Communications

First record of the sea slug *Lobiger serradifalci* (Calcara, 1840) (Gastropoda: Sacoglossa: Oxynoidae) from the Indian coast

– Dimpal Dodiya & Paresh Poriya, Pp. 26553–26557

Impatiens damrongii (Balsaminaceae), a new record for the flora of Vietnam

– Ha Van Dang, Leonid Vladimirovich Averyanov & Cuong Huu Nguyen, Pp. 26558–26561

Invasive record of Brazilian *Petunia Ruellia elegans* Poir. (Acanthaceae) from northeastern India

– Mamita Kalita, Pp. 26562–26565

Note

Cuphea carthagenensis (Jacq.) J.F. Macbr. (Lythraceae)

— a new non-native plant record for the Eastern Ghats of India

– Prabhat Kumar Das, Bishal Kumar Majhi, Shashi Sourav Hansda, Samarendra Narayan Mallick, Purnendu Panda & Pratap Chandra Panda, Pp. 26566–26570

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