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Paving the way for a holistic conservation Approach: The story of World's only known simple frond tree Fern, *Alsophila sinuata* (Hook. & Grev.) R. M. Tryon (Cyatheaceae)

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ABSTRACT

Island endemics are significant due to their unique genetic composition and their vulnerability to a high risk of extinction. The tropical island, Sri Lanka, harbors approximately 389 pteridophyte species. Among them, tree ferns (Cyatheaceae) are considered an important and isolated gene pool in the Indian Ocean. Among the nine tree fern species, including five endemics (71%), *Alsophila sinuata* is interesting due to its unique simple fronds and its narrow distribution pattern, comprising a few restricted populations across the southwest lowland rainforests of Sri Lanka. The species is classified as Endangered (EN) due to its restricted distribution pattern, small population size, and the threats it faces. The holistic conservation approach is one of the most effective and efficient strategies for conserving such narrowly distributed, threatened, and isolated populations. This review summarizes and analyzes all published and unpublished information, along with personal observations of the authors, while providing baseline information for the application of a future conservation approach to safeguard this interesting species.

1. Introduction

Islands, with their discrete territories and abundant biodiversity, hold great interest for conservationists (Fois et al., 2020). Islands are especially likely to be "speciation laboratories" and to facilitate the development of novel adaptations and new species (Franks et al. 2010). Island biodiversity is changing with some species going extinct, others changing in abundance, non-native species becoming a part of many ecosystems, and humans shaping many ecological processes (Russell and Kueffer, 2019). The flora of isolated continental islands faces a significant risk of extinction, making their conservation the biggest challenge we currently face (Russell and Kueffer, 2019; Cowie et al., 2022).

Sri Lanka is a tropical and continental island harboring and preserving unique biodiversity while playing a key role as part of global biodiversity. Being a part of the Western Ghats-Sri Lanka global biodiversity hotspot, the country shows its great significance within the global biological diversity (Perera and Fernando, 2022). Pteridophytes are a vital component of Sri Lankan biodiversity, contributing to approximately 11 % (350 taxa) of the island's native vascular plant species including 42 taxa considered as island endemics (Ranil et al., 2022). The vulnerability of island flora to a high risk of extinction is evident. This is demonstrated by the identification of 207 pteridophyte taxa as threatened, along with 25 pteridophyte and 128 angiosperm species classified as critically endangered or possibly extinct (Ranil et al., 2020; Redlist, 2020).

Though the number of species is relatively small (9 species), Sri Lankan tree ferns have long been the subject of fascination for taxonomists due to their biogeographic significance, diversity, and endemicity compared to the land size, as well as some unique morphological characteristics (Ranil et al., 2017). Most species exhibit highly specific and narrow distribution patterns locally. However, except for two naturalized species, other seven species including five endemics treated as nationally threatened species (Ranil et al., 2020). Of these, *Alsophila sinuata* (Hook. & Grev.) R. M. Tryon stands out due to its unusual simple fronds, unique plant habit, local endemism, and narrow eco-geographic distribution pattern. Although the species is primarily distributed within the country's protected area network, due to its restricted population size and limited geographical and ecological adaptability, *A. sinuata*

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poses a significant risk of extinction (Redlist, 2020; Ranil et al., 2011). Consequently, there is a pressing need for conservation efforts to ensure its conservation within the natural ecosystems.

The information on population dynamics is a primary need for taking decisions on future conservation. For example, Paul et al. (2015) studied population structure and regeneration status of *Gymnosphaera gigantea* (Wall. ex Hook.) J.Sm., an endangered tree fern in India and reported that effective conservation strategies are therefore to be formulated to save the species from the threat of extinction in the near future. Ju et al. (2014) also studied *Alsophila spinulosa* (Wall. ex Hook.) R.M. Tryon in southwest China and they suggested that the *A. spinulosa* population had the capacity for natural regeneration, but human interference might limit its population density. These studies have emphasized the necessity of studying on structure, composition, and regeneration status of tree fern species for formulating conservation plans.

Developing species recovery plan or management plan for many species is a challenge due to insufficient basic information on their taxonomy, ecology, distributional patterns, population dynamics, reproductive biology, and threat status (IUCN/SSC, 2008). This limitation significantly hinders the adoption of a holistic conservation approach for species conservation. However, in comparison to other pteridophyte species in Sri Lanka, *A. sinuata* stands out with adequate baseline information, making it suitable for the development of a conservation plan following a holistic conservation approach. To support conservationists and policymakers in this endeavor, we have compiled and analyzed all available published and unpublished information on *A. sinuata*, incorporating the research experience and observations of the authors on this unique species over the past two decades. We are confident that the information presented here will make a significant contribution towards safeguarding the in-situ populations of *A. sinuata* and provide valuable guidance for implementing *ex-situ* conservation approaches as well.

2. Materials and methods

This review covers a comprehensive analysis of both published and unpublished literature (thesis, technical reports and field notes) pertaining to *A. sinuata*, combined with the authors' observations and field experience gained through their involvement in two projects focusing on Sri Lankan tree ferns between 2006 and 2013. Furthermore, the investigation incorporates valuable insights derived from subsequent field explorations and observations conducted up until 2020. The article provides summarized information with the aim of aligning it with the development of a future management and conservation plan for *A. sinuata*. Additionally, a detailed taxonomic description was developed by considering a wide range of morphological variations and a distribution map was developed as explained below.

2.1. Taxonomic description

The botanical description developed for this review is primarily based on the authors' field observations and micro and macro morphological analysis of collected specimens (currently deposited at the PDA) during the study period. In addition, the previously made descriptions Hooker & Gerver (1831), Hooker (1844) Thwaites (1864) Beddome (1864; 1883), Holttum (1965), Large and Braggins (2004) and Pillcox (2006) were also studied and considered.

2.2. Geographical distribution

A new distribution map was developed for this review based on localities provided in the literature and herbarium specimens collected by the authors, as well as both local and foreign botanists over the last century. The distributional records were given by Philcox (2006) and digital images and records of virtual herbaria as well as two major online data repositories (https://www.pteridoportal.org and https://www.gbif.org) were also used to map the distribution pattern. The physical examination of specimens at the PDA, SING, K, and AK was also incorporated. Over 100 specimens deposited at the 22 worldwide herbaria (P, K, E, BM, L, BR, LD, NL, UC, MICH, US, F, LIV, USCH, MSC, BRU, PDA, K, AK, SING, MO, NY), 44 records were used to prepare the distribution map. Given the lack of precise locality information in the majority of herbarium records, this analysis considered the known nearest localities while disregarding poorly cited herbarium specimens. The specimens that have also been recorded from the same locality did not include in this analysis. The QGIS (3.28.3) software was employed for preprinting the distribution map.

3. Results and discussion

First, we provide all viable information on *A. sinuata*, along with a detailed analysis. We then offer guidelines for developing a conservation plan aligned with the principles of a holistic conservation approach.

3.1. Taxonomic treatment

The protologue of *A. sinuata* was initially limited to a few characteristics (Hooker and Greville, 1829). Later, Hooker (1844), Thwaites (1864), and Beddome (1864; 1883) added a few more characters and illustrations. However, the description provided by Holttum (1965) offers a much broader understanding of the plant compared to previous descriptions. Large and Braggins (2004) also provided a brief account along with a color photograph. The description given by Pillcox (2006) is more detailed, but it relies entirely on previously collected herbarium specimens, thus not capturing the entire morphological variation.

Accurate species identification is indeed a fundamental aspect of any conservation plan. Misidentification or uncertainty regarding species identification can lead to ineffective or inappropriate conservation measures. Therefore, ensuring accurate species identification is essential for the success of conservation efforts. With that in mind, a detailed botanical description for *A. sinuata* is provided here, primarily based on recently collected specimens from *Sinharaja* World Heritage Site (Sinharaja WHS), Kanneliya Man and Biosphere Reserve (*Kanneliya* MAB), *Hinidum Kanda*, *Beraliya Mookalana*, and *Morapitiya-Roonakanda* forest reserves.

Alsophila sinuata (Hook. & Grev.) R.M. Tryon, Contr. Gray Herb. 200: 32 (1970). (Figs. 1–4).

= *Cyathea sinuata* Hook. & Grev. in Icon. Filic. 1: t. 106 (1831) (Fig. 1).

≡ Schizocaena sinuata J.Sm. in London J. Bot. 1: 661 (1842).

Type:—SRI LANKA. Pas-dum-Karle [=Korle], 1827, Emerson s.n. (holotype E00385940). (Fig. 2).

Description:— Trunk erect, occasionally slant or decumbent, bushy, with prominent single tree, 2–10 well grown offshoot arise form trunk base, usually with 1–6 adventitious shoots along the trunk, usually unbranched, rarely branched, (–0.5) 0.7–1.7 (–2) m in height, 1.3–1.6 cm in diameter, entirely covered by persistent dead petiole bases, frond scars not visible. Petiole dark blackish brown coloured, shiny, 3.5–4.1 cm long, 0.2–0.4 cm in diameter at its base. Petiole spines slightly or absent, blunt, 0.1–0.05 cm long. Petiole scales, 0.05–0.1 cm long, 0.3–0.4 cm wide at their base, dark brown, linear to narrowly triangular, with an apical spine, margin sometime with several conspicuous dark setae, scales densely covering the younger fronds. Fronds 20–32 in number, crowded at the end of the stem with conical or umbrella shaped crown. Crown width 70—120 cm. Lamina 45–70 cm long, 2.3–3.3 cm wide, linear, light green adaxially, olive green abaxially, subcoriaceous to coriaceous, rachis dark brown and shiny, glabrous adaxially, simple, linear. Scales few in lower surface, associated with lateral veins, dark brown, convex to bullate. Margin entire or sinuate to 1–2 mm towards rachis or dentate to 2–4 mm towards rachis. Apex gradually decrescent, acuminate, serrated or sinuate margin. Base gradually reduced, ending with sinuatae or entire margin or shallowly deep lobes. Rachis grooved

Fig. 1. (Left). The botanical drawing of *Alsophila sinuata* ().
adopted from the Icones Filicum (1831) authored by W.J. Hooker and R. K. Greville.

Fig. 2. (Right). The type specimen of the *Alsophila sinuata* collected be Emerson in 1827 ().
available at https://data.rbge.org.uk/herb/E00385940

and dark brown adaxially, light brown abaxially, glabrous. Veins 3–5 pairs, free, reaching the margin. Sori 3–5 pairs, inframedial, indusiate. Indusium thin, initially covering sorus, irregularly splitting, persistent, forming uneven cap.

3.2. Morphological variation

Alsophila sinuata shows a wide range of morphological variation within their natural habitats. This variation has initially identified by Manton and Sledge (1951). Then Ranil (2010) and Ranil et al. (2010) further noted such variation and have been carried out a detailed investigation. According to them, *A. sinuata* is clustered into two sub-groups, which can easily differentiate one group from the other using deeply sinuate frond margin, and irregular or global or umbrella shape crowns with drooping fronds at first glance (Fig. 4A & B). The number of veinlets, sori arrangement, and the number of pair of sori also help to distinguish these two groups. It has reported the sixteen morphological differences between these two variations. Having local forms of Sri Lankan ferns is rather common, perhaps due to being an island, long-term geographical and reproductive isolation. Since this is the initial step of the sympatric speciation process, continuous monitoring of such variations within their natural habitats is important. However, during the subsequent observations, we realized that these two morphotypes proposed by Ranil et al. (2010) shared some characteristics and formed other variable types under different climatic and habitats. Thus we meaningfully integrated all such variations and presented them here under typical *A. sinuata*.

Recognizing the factors that drive morphological variations in a species within natural ecosystems presents a significant challenge. Nonetheless, studying such variations can provide valuable insights into the evolutionary pathway and speciation processes of a particular species. *Alsophia sinuta*, along with its close relatives, *A. hookeri* and *A. sledgei*, often co-occur and share certain morphological characteristics (Key 1). It is possible that some of the observed morphological forms may be hybrids resulting from the close affiliation between these species. Sledge (1981) described a number of endemic *Trigonospora* species from Sri Lanka that also co-occur with each other. However, Fraser-Jenkins et al. (2016) and Ranil et al. (2016) reported some of these species as local forms of one or two particular species. The presence of such local forms is not uncommon, given the co-occurrence of closely related species particularly among the island flora. This phenomenon may signify an initial step in the speciation process. Consequently, continuous monitoring and evaluation of such occurrences are crucial in the field of evolutionary biology.

Key 1: Key to the three co-occurring *Alsophila* species in Sri Lanka.

1. Lamina simple or pinnatifid, less than 90 cm long, 2–5 cm wide ……..**2**
1. Lamina simply pinnate, 92–118 cm long, 21—28 cm wide……***A. hookeri***
2. Lamina simple, margin entire or sinuate, 45–70 cm long, 2.3–3.3 cm wide……***A. sinuata***

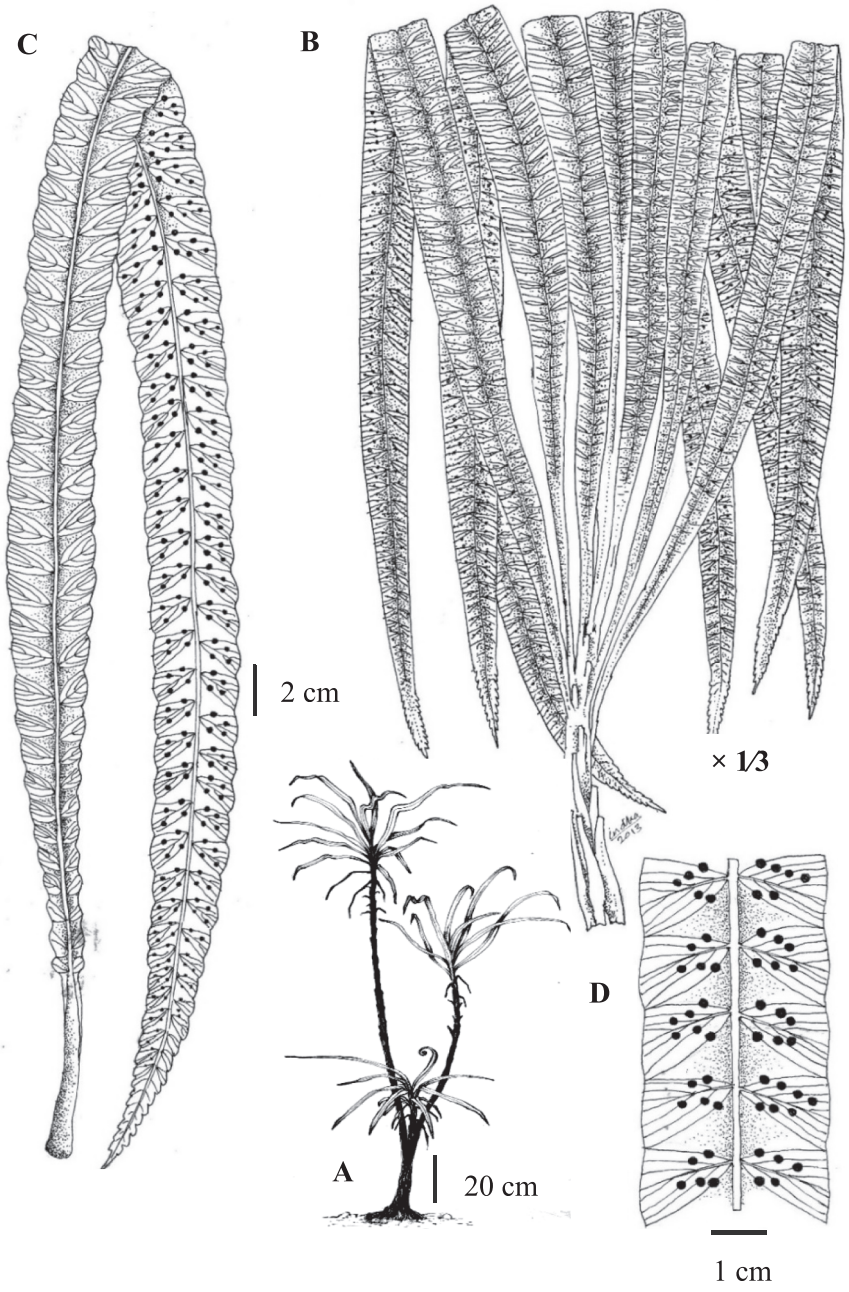

Fig. 3. Morphological characteristics of *A. sinuata*. A. plant habit. B. collection of fronds. C. a single frond. D. sori arrangement.

2. Lamina pinnatifid, deeply lobed, 60–90 cm long, 3.0–4.2 cm wide……..***A. sledgei***

By conducting ongoing monitoring and assessment of these incidences, researchers can gain valuable insights into the dynamics of morphological variation, hybridization, and potential speciation events. Therefore, it is essential to emphasize the importance of continuous monitoring and evaluation of *A. sinuata in* the field of evolutionary biology.

3.3. Geographical distribution

Alsophila sinuata is endemic to Sri Lanka. Large and Braggins (2004) have erroneously mentioned its occurrence in South India. According to the previous records, *A. sinuata* was restricted to the *Sinharaja* WHS (*Ratnapura* and *Matara* districts) and *Kanneliya* MAB reserve (*Galle* district). During our exploration of tree ferns in Sri Lanka since 2006, we were able to discover a few small populations from the *Beraliya* forest reserve, *Hinidum kanda* forest reserve, and *Morapitiya- Runakanda* forest reserve (Ranil, 2013). However, this observation is not surprising, as these forest reserves were originally linked to *Sinharaja* WHS and *Kanneliya* MAB reserves. The map also very clearly shows that *A. sinuata* is confined to the southwest rainforests of the wet zone of Sri Lanka (Fig. 5).

Banik et al. (2023) report that if the species has fragmented populations and smaller patch sizes, the conservation of study species will require an integrated landscape as well as local-scale geospatial habitat management strategies to protect the natural populations and enhance the distributional range. Furthermore, they have a well-explained use of GIS technology and statistical modeling for identifying geospatial distribution and probability areas of *Gymnosphaera gigantea* (Wall. ex Hook.) S.Y.Dong in India. Since, *A, sinuata* is also demonstrating such a

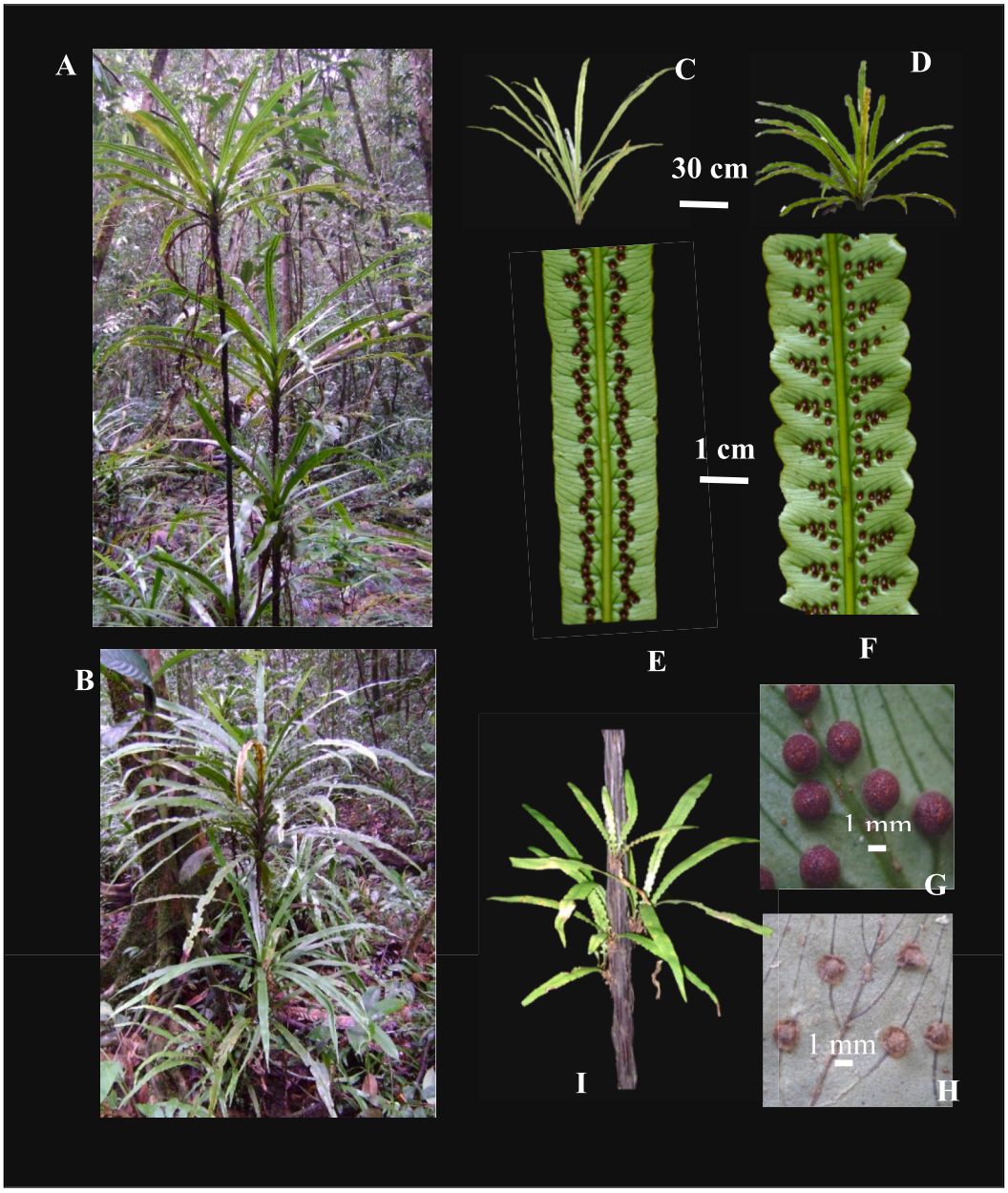

Fig. 4. Botanical characteristics of *A. sinuata*. A: plant habit with conical shape crown. B: plant habit with umbrella shape crown. C: conical shape crown. D: umbrella shaped crown. E: sori arrangement of slightly sinuate frond. F: sori arrangement of deeply sinuate frond. G: sori before opening sporangia. H: sori after opening sporangia showing the receptacles and indusia. I: adventitious shoots on main trunk.

scattered and small population, the use of advanced methods (mathematical modeling, mapping of probability areas, ect.) will support for discovering new populations from nearby forest reserves as well as identifying similar vegetation types and habitats of other forest areas within the lowland rainforest complex.

3.4. Phylogenetic and biogeographic significance

As Holttum (1965) identified nearest allies of *A. sinuata* are *Alsophila borbonica* (Desv.) R.M.Tryon (Syn: *Cyathea borbonica* Desv.) and allied species in Madagascar and other islands of the Indian Ocean. Holttum's hypothesis on phytogeographical affinities of Sri Lankan tree fern species with African elements is not aligned with recent studies (Korall et al., 2007; Janssen,et al., 2008; Korall and Pryer, 2014). It appears that Sri Lankan tree fern species form a monophyletic group and have no relation with African elements. Hence, Sri Lankan tree fern species can be considered as an important and unique genetic pool to be conserved. However, it is important to further genomic studies including whole genome sequencing to elucidate its genetic makeup and evolutionary history which support further conservation efforts.

3.5. Habitat and ecological requirements

The habitat of *A. sinuata* can be defined as terrestrial and it typically found along stream banks (Fig. 6E), particularly by the spray zones of fast-flowing streams. This preference for moist conditions indicates its affinity for areas with humid and partially shaded environments. It also showed scattered distribution pattern. The both *Sinharaja* WHS and *Kanneliya* MAB reserve have well connected perennial and seasonal stream network while creating spray zones near streamside banks. Ranil et al. (2007) and Sedayu (2006) also found that *A. sinuata* are highly colonized in streamside banks with high moist areas and becomes scarce

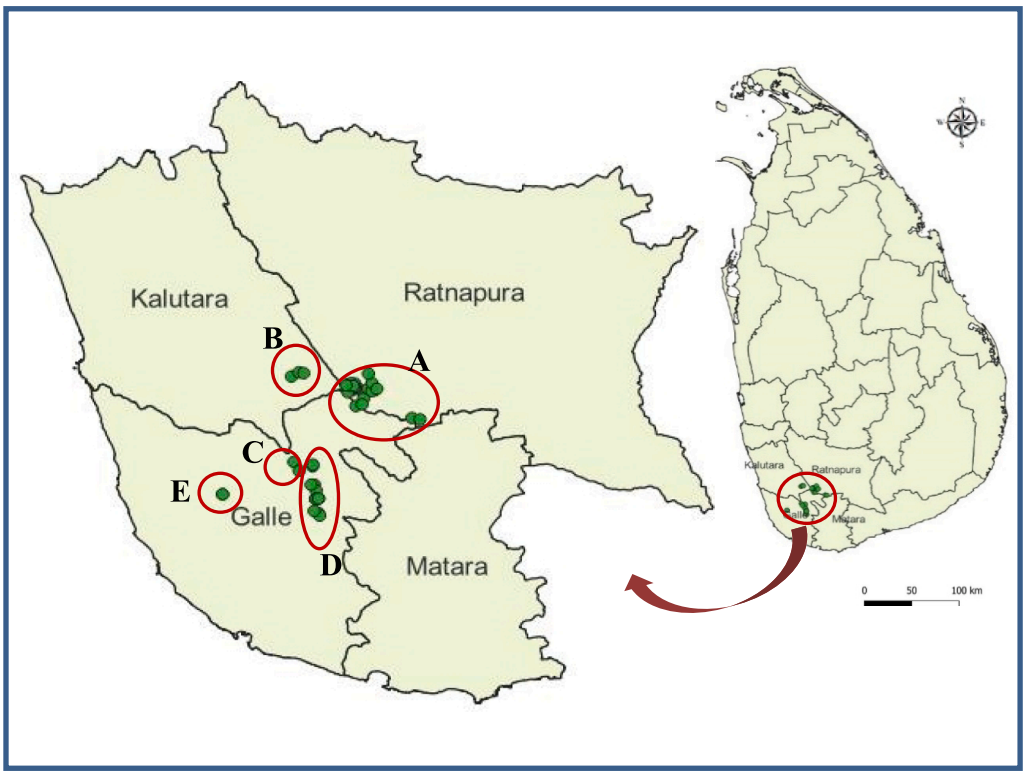

Fig. 5. The distribution patterns of *A. sinuata* in south-west lowland rain forests of Sri Lanka (A- Sinharaja WHS; B- Morapitiya-Roonakanda forest reserve; C- Hinidum Kanda forest reserve; E- Beraliya forest reserve). **Note:** The green-colored dots indicate the locations of *A. sinuata* used for mapping, while the red-colored circles approximately demarcate the boundaries of each forest reserve where the species was reported.

with increasing elevation. Even though, tree ferns are typically terrestrial, some individuals of *A. sinuata* were observed as lithophytic habitats on immediate vicinity in rocky streamside banks (Fig. 6 A, B, C). As we observed, this species is mostly co-occurring with its nearest allied species, *Alsophila hookeri* (Thwaites) R.M. Tryon and *Alsophila sledgei* (Ranil, Pushpak. & Fraser-Jenk.) Ranil (Fig. 6D). The main trunk is supported for growing of small epiphytic ferns and bryophytes (6F). Ranil (2010) provide detail information on most preferable climatic (temperature, rainfall, light level, canopy cover) and soil characters (N, P, K, pH, electrical conductivity, organic carbon and organic matter) for natural distribution of *A. sinuata* in two forest reserves (Table 1).

Based on the results of the above study and our further observations, it can be stated that both *Sinharaja* WHS and *Kanneliya* MAB provide the most favorable and unique microenvironment for this species compared to small populations found in other three forest reserves. Except for the annual rainfall, all other ecological parameters are more or less similar in both forests. Relatively high rainfall may be the main reason for the comparatively higher density of *A. sinuata* in *Sinharaja* WHS than in the *Kanneliya* MAB. It is generally accepted that water availability is the determinant factor to decide population density and distribution of pteridophytes because the reproductive system is largely dependent on the availability of external water (Soltis et al. 1991).

Gaining a comprehensive understanding of the ecology of a specific species is a complex process that requires both time and a deep level of analysis and observation. Therefore, further studies need to focus on the long-term evaluation process of its ecological requirements, along with population dynamics. However, the available information can be effectively utilized as a baseline for future studies and for developing conservation guidelines.

3.6. Population structure and regeneration

Alsophila sinuata shows an isolated and discontinued distributional pattern associated with the stream network. Usually, high-density colonies are formed along the streamside banks and each population observed demonstrates relatively high regeneration (Ranil, 2010). Though *Sinharaja* WHS consists of a considerable number of isolated populations with more individuals, the other four forest reserves have a few populations with low density. The height class distribution pattern of *A. sinuata* of 35 subplots in *Sinharaja* WHS and *Kanneliya* MAB reserve has been studied by Ranil (2010). The researcher has reported that all populations show the highest density of juvenile plants than mature individuals (Fig. 7). Our recent observations were also evident that natural regeneration is continuing without any external disturbances.

3.7. Reproductive biology

The study of reproductive biology on ferns is new to Sri Lanka, although it plays a key role in conservation strategies. Even within the global context, information on the reproductive aspects of tree ferns is scanty (Conant, 1990; Chiou and Ying, 2000; Khare et al., 2005; Chen et al., 2008; Khare and Srivastava, 2009; Rechenmacher et al., 2010). Ranil et al. (2010) studied on gametophyte morphology of *A. sinuata* and its two co-occurring taxa and provide some details on spore germination, gametophyte morphology, sexual expression, and sex ratio. Spore germination of *A. sinuata* started 7–10 days after spore sowing. They further highlighted that it shows 32.9 % (±7.4) of germination percentage and spore viability will be lost after 28 days of releasing from sporangia. Furthermore, the authors do have an experience in the cultivation of individuals raised from spores as well as plants transferred from the wild to the indoor environment (Fig. 8).

In addition to gametophyte morphology, the study conducted by Ranil et al. (2010) lacks detailed and comprehensive information regarding the development of antheridia and archegonia, as well as the fertilization process in *A. sinuata*. However, the available information

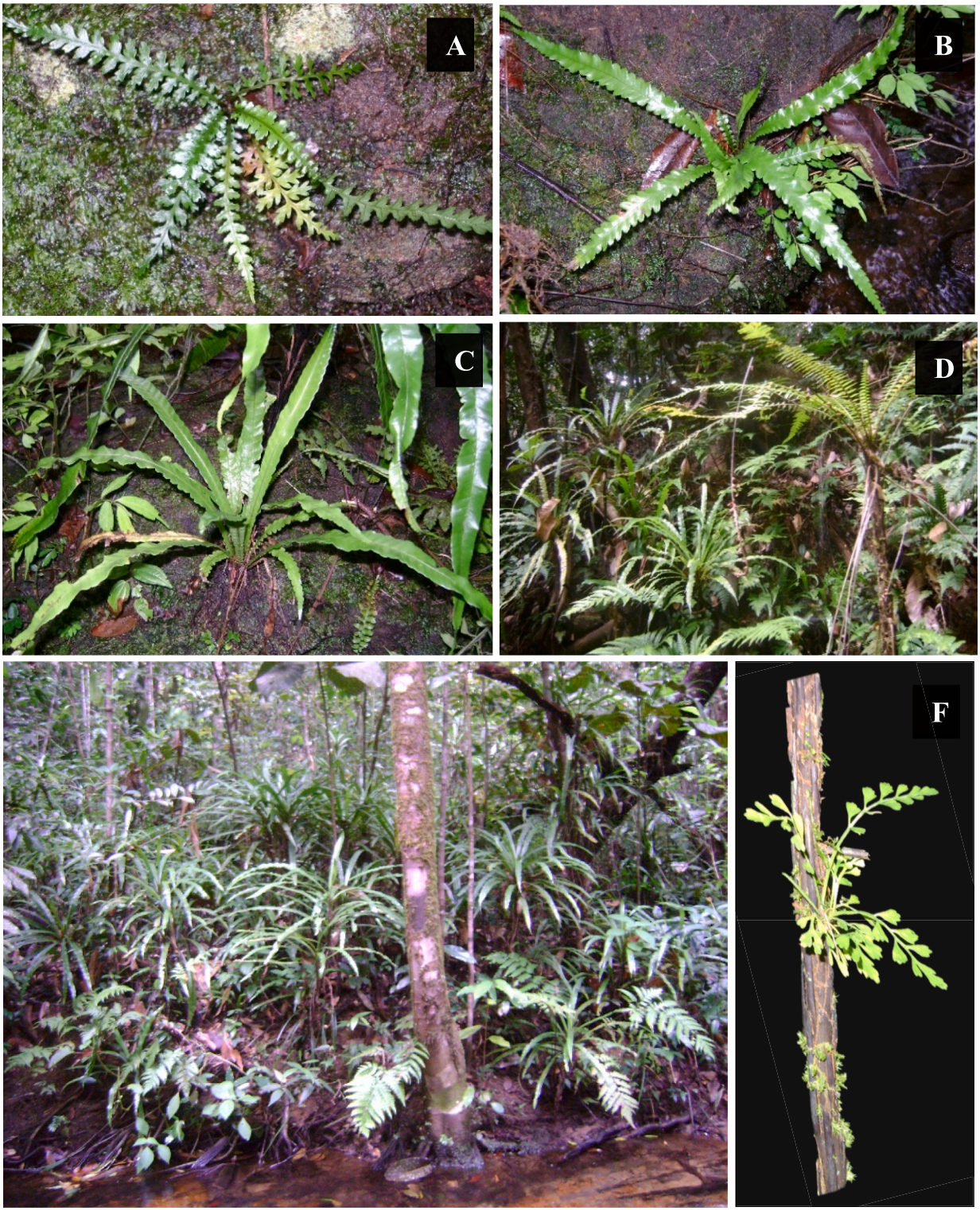

Fig. 6. Habitats *A. sinuata*. A, B and C: juvenile plant with pinnatifid fronds, deeply sinuate fronds, slightly sinuate fronds on moist and mossy rocks, respectively. D: a *A. sinuata* is co-occurring with *A. hookeri*. E: a densely grown population nearby stream. F: an epiphytic fern and bryophyte species grown on main trunk. Note: At the early stage of sporophyte development, some fronds rarely exhibit pinnatifid characteristics (Fig. 6A).

serves as a fundamental basis for the development of both *ex-situ* and *in-situ* conservation strategies for this species, while also guiding future research directions. It also worthy to mention that the mass propagating scaly tree ferns can be achieved through the use of their spores. Employing spore culture represents the most effective strategy for conserving the species *ex-situ*. Shukla and Khare (2012) provide detail information on *in-vitro* mass multiplication of a threatened tree fern, *Alsophila spinulosa* (Wall. ex Hook.) R.M. Tryon. Conducting further studies on the reproductive biology of *A. sinuata* would not only shed light on its regeneration patterns and abundance in natural ecosystems but also provide valuable insights for the conservation of the species both *in-situ* and *ex-situ*.

Table 1
Preferable ecological requirements for *Cyathea* species.

Ecological parameters	Mean value Sinharaja WHS	Kanneliya MAB
Light level (Lux)	$3,248^{a} \pm 2,468$	$1,235^{b} \pm 449$
Canopy cover (%)	$46^{a} \pm 28$	$79^{a} \pm 3$
Organic matter (%)	$4.5^{a} \pm 1.9$	$3.9^{a} \pm 1.2$
Organic carbon (%)	$2.4^{a} \pm 0.9$	$1.6^{a} \pm 0.6$
N (mg/g^{-1})	$1.5^{a} \pm 0.5$	$1.2^{a} \pm 0.6$
P(mg/g^{-1})	$0.03^{a} \pm 0.01$	$0.04^{a} \pm 0.03$
K(mg/g^{-1})	$0.04^{a} \pm 0.02$	$0.03^{a} \pm 0.05$
pH	$5.1^{a} \pm 0.2$	$5.5^{a} \pm 1.0$
EC (us)	$62^{a} \pm 25$	$60^{a} \pm 31$

Note: Table shows mean value of each parameter with standard deviation and same superscript letters of each row indicates no significance at $P < 0.05$. Adopted from Ranil (2010).

3.8. Conservation status

Alsophila sinuata is treated as an endangered species under the National Red List- 2020. Furthermore, it has adequate legal coverage being listed in the Fauna and Flora Protection Ordinance in Sri Lanka and in Annex II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora. Since all reported populations are confined to the country's protected area network, the conservation status will not be changed unless the area of occurrence expands due to the discovery of new populations with a significant number of individuals. Being designated as UNESCO World Heritage Site and International Man and Biosphere reserve, two major populations are in both *Sinharaja* and *Kanneliya* forest reserves receive special attention and legal protection. Thus, no anthropogenic threats have been observed thus far in the natural population of *A. sinuata* in those two forest ecosystems.

However, other locations may face potential treated due to anthropogenic factors, including illegal encroachment, habitat disturbance, excessive visitation, and occasional collection of species from the wild due to its high ornamental value. Discussions with residents from nearby villages revealed that they have observed a declining population of all tree ferns over the last few decades. These observations were subsequently confirmed by some forest officers as well. Moreover, future climate change events may impact the population dynamics of this species due to their high sensitivity to changes in microclimate. The development of a conservation and management plan is thus timely and crucial, addressing not only the specific species but also the entire tree fern group in Sri Lanka.

3.9. Formulation of a conservation and management plan for a. Sinuata

The effectiveness of a conservation and management plan for a particular ecosystem or species is mainly determined by the extent of integration of different perspectives. While academic disciplines play a key role in conservation planning, the contributions from other perspectives, such as intellectual domains, socio-economic aspects, and the involvement of academia, administrators, and the public, are also significant. Conservationists and policymakers have a crucial role in selecting, prioritizing, and integrating the most appropriate perspectives, with the aim of formulating a holistic approach for the conservation and management of individual taxa or entire ecosystems.

Given that *A. sinuata* is restricted to the country's protected area network and receives legal protection through various local and international acts and ordinances, the species faces minimal threats from anthropogenic factors. Since the species does not have economic potential, the peripheral community does not show a strong interest in it. Thus, instead of adopting an individual species conservation approach, the conservation plan needs to focus on safeguarding the entire ecosystem. In this regard, government institutes aligned with forest and wildlife conservation should have a major responsibility in enforcing existing policies and formulating new ones.

The economic potential of *A. sinuata* remains underestimated. In the authors' personal opinion, the species has a high potential to be developed as an ornamental plant. It is worth mentioning that the current Sri Lankan floriculture industry is predominantly focused on exotic ferns, and local fern species have not received much attention from floriculturists. However, considering *A. sinuata's* status as an endemic, threatened, and protected species, introducing it into the floriculture industry poses a challenge. Nonetheless, in order to realize the concept of conservation through utilization, certain decisions need to be made with the support of policymakers and relevant administrative bodies.

Since the species is highly confined to particular habitats with unique microclimates, *ex-situ* conservation presents a challenge. However, this review provides some basic details and guidelines for *ex-situ* cultivation, and we successfully maintained an *ex-situ* population in a net house until they reached the reproductive stage. Subsequently, we transferred all individuals back to their natural habitats. Hence, it is important to develop a micropropagation protocol for mass production of *A. sinuata*, with the aim of translocating them to the appropriate natural habitats.

It is noteworthy to mention the cytological investigation of Sri Lankan ferns conducted by Manton and Sledge (1954). They reported the successful establishment of five cyatheaceous tree ferns from Sri Lanka through cultivation. Furthermore, they specifically mentioned that the cultivation of *A. sinuata* and *A. hookeri* is most difficult due to their habitat specificity, and they recommended a saturated atmosphere for several months when first transplanted. Apparently, they had been

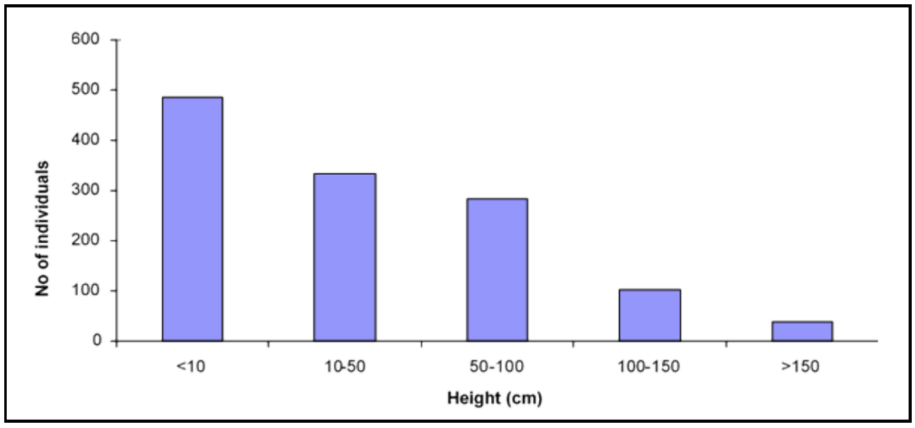

Fig. 7. Height class distribution of both mature and immature A. sinuata plants in 35 subplots (25 m^2 x 35 = 875 m^2).
Adopted from Ranil (2010)

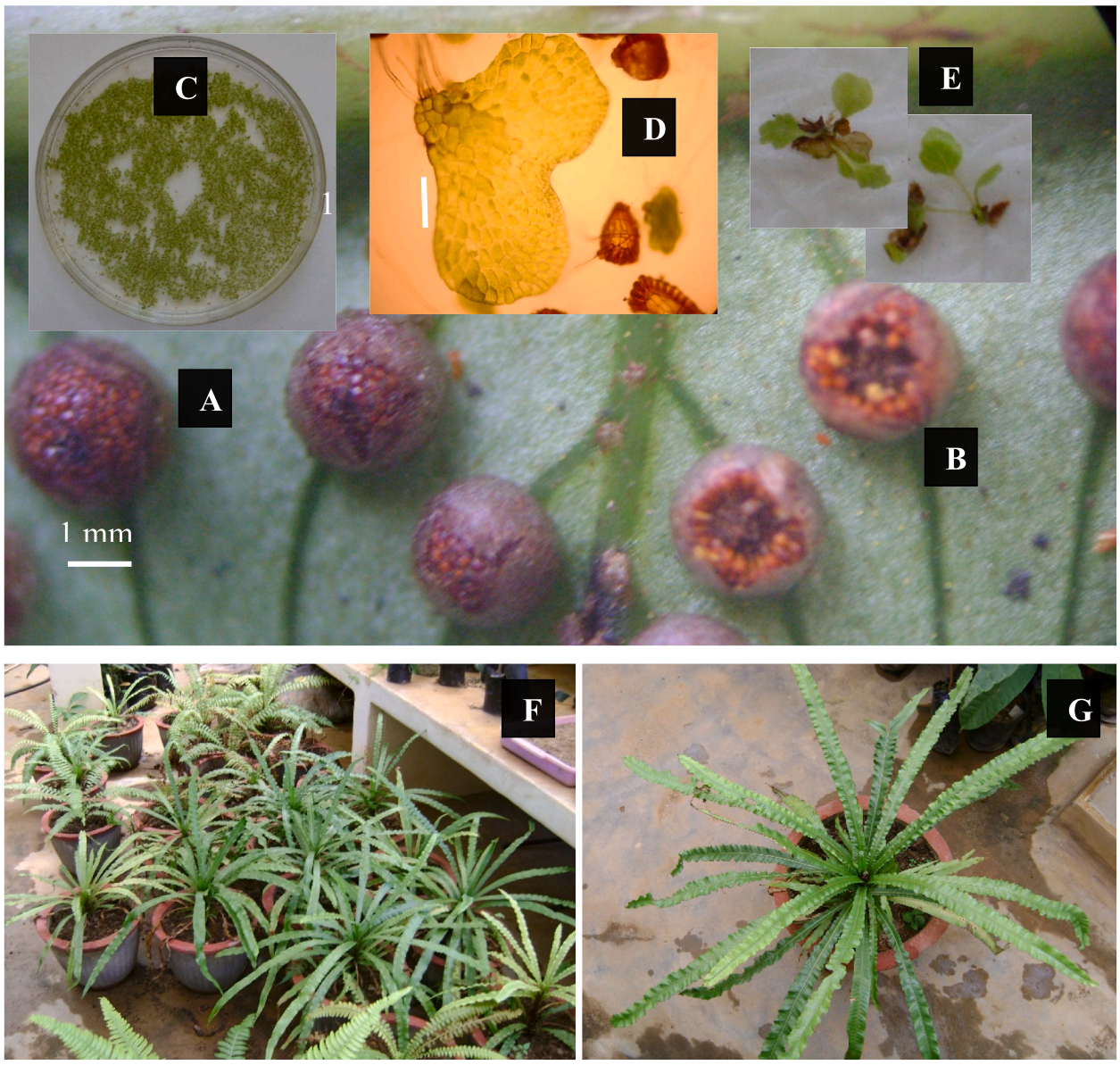

Fig. 8. Different stages of life cycle of *A. sinuata.* A. a sorus with unopened sporangia. B. a sorus with ruptured sporangia. C. germinated spores (2 weeks after spore sowing (WAS)). D. gametophyte (4 EAS). E. six weeks old sporophytes. F and G. *ex-situ* population maintained (approximately 50) in the net house at the Department of Crop Science, Faculty of Agriculture. University of Peradeniya (later transferred to their natural habitat).

cultivated these species at the University of Leeds or the Royal Botanic Gardens, Kew. Our experience on *ex-situ* cultivation of *A. sinuata* aligns with their observations, highlighting its potential and adaptability in an *ex-situ* environment. However, due to its climatic sensitivity and habitat specificity, it is important to explore potential intermediate conservation approaches, such as *quasi in-situ* or *circa situm* (Heywood et al., 2018), for the conservation of *A. sinuata* outside of its natural habitat.

Ex-situ conservation is important not only due to its conservation value and scientific merit but also because of its contribution to disseminating knowledge about the biological wealth and conservation significance of endangered species. Public awareness plays a major role in any species recovery or conservation plan. Therefore, maintaining *ex-situ* collections is important to enhance public awareness of rare species and their conservation, usually which falls under the mandate of botanic gardens. Currently, *Hakgala* Botanic Garden in Sri Lanka successfully maintains the *ex-situ* populations of two native tree fern species (*Alsophila walkerae* (Hook.) J.Sm. and *Sphaeropteris crinita* (Hook.) R.M. Tryon) along with a few exotic tree fern species. However, the current setup of ferneries in Sri Lankan botanic gardens needs significant modification to accommodate the *ex-situ* conservation of *A. sinuata* and its co-occurring species.

The active involvement of all stakeholders, including researchers (universities and research institutes), administrators (such as the Forest Department, Department of Wildlife, Botanic Gardens, etc.), and the general public (particularly the peripheral communities living around the forest reserve with the candidate species) is essential for developing a strategic plan to conserve *A. sinuata* within its natural ecosystem. Therefore, conservationists and policymakers need to play a key role in actively engaging all stakeholders in the conservation mission.

4. Concluding remarks

The effectiveness of the conservation plan is primarily based on the information available in all relevant disciplines. The knowledge of Sri Lankan pteridophytes is mostly restricted to checklists, monographs, and morphological descriptions. Therefore, conservationists and

policymakers have faced trouble in developing conservation and management plans due to a lack of information on distributional ecology, habitat requirements, population dynamics, reproductive biology, and genetic markup of species. However, among the diverse fern flora of Sri Lanka, tree ferns stand out due to their rich basic information as a result of two comprehensive studies carried out from 2006 to 2013. This article summarized all published and unpublished information aligning with the holistic conservation approach of *A. sinuata*. Also, it highlighted that the areas need to be further studied.

This review provides a comprehensive analysis of the morphological variations observed in the species under its natural growing environment. These variations may be attributed to multiple factors, including adaptation to specific ecological niches, reproductive isolation mechanisms, and the influence of habitat heterogeneity, etc. Importantly, these findings highlight the need for further investigation into the speciation process associated with *A. sinuata*. Furthermore, this review provide useful information on ecological requirements, most preferable habitats, and population distribution of *A. sinuata* up to a certain extent. However, studying and long-term monitoring of its population is suggested to further understand the population dynamics of this interesting species with the support of information generated from this study. Further, evaluation and continuous monitoring of the ecology and habitat characteristics of selected populations are required to identify effective and efficient conservation strategies. It is also important to further extend the studies on reproductive biology and natural regeneration of *A. sinuata* which is the most crucial factor in the conservation approach of any species.

We hope that this information will provide adequate support to develop a species recovery plan or management and conservation plan for existing populations in the aforementioned forest reserves in the south-west of Sri Lanka. Additionally, this information provides guidelines for the mass propagation of *A. sinuata* using spores followed by translocating into suitable natural habitats of Sri Lanka.

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R.H.G. Ranil: Conceptualization, Data curation, Writing – original draft, Investigation, Validation, Formal analysis, Methodology. **D.K.N. G. Pushpakumara:** Conceptualization, Writing – review & editing, Validation, Methodology. **D.S.A. Wjesundara:** Conceptualization, Writing – review & editing, Validation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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