



RESEARCH ARTICLE

Drivers of invasion: The spread of pink-flowered *Nymphaea rubra* Roxb. ex Andrews in paddy ecosystems of Kuttanad, South India

Devi V S^{1*}, Nimmy Jose² & Sona Sebastian¹

¹Regional Agricultural Research Station, Kerala Agricultural University, Kumarakom, Kottayam 686 563, Kerala, India

²M S Swaminathan Rice Research Station, Kerala Agricultural University, Moncompu, Alappuzha 688 503 Kerala, India

*Correspondence email - devi.vs@kau.in

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Abstract

Kuttanad, the rice bowl of Kerala, is a unique agro-ecosystem practising below-sea-level farming, declared as a globally important agricultural heritage system by the Food and Agriculture Organisation (FAO) in 2013. Its paddy landscapes and waterbodies face severe aquatic weed invasion, intensified by nutrient influx due to leaching from surrounding paddies and high inherent soil fertility. Since the 2018 flood, pink-flowered waterlilies (*Nymphaea rubra* Roxb. ex Andrews) have spread widely, producing substantial biomass-about 65300 kg ha⁻¹ fresh weight. Infestation occurs during rice fallow when fields remain inundated, delaying land preparation for the next crop. At the same time, the bloom is promoted as a hub for waterlily tourism. A study in the Malarikkal region of Thiruvarp Panchayat, Kottayam, investigated the biology and growth dynamics of the invasive pink waterlily *N. rubra* and the native *Nymphaea pubescens* to identify drivers of proliferation. Experiments assessed flowering behaviour, biomass and the influence of rhizome size on plant morphology under controlled conditions. A field investigation from June to September 2024 documented seedling emergence, growth stages and morphological traits across varying water depths, revealing how flooding and depth gradients affect the propagation and blooming of the species. *Nymphaea rubra* is a night bloomer, opening at 6.00 pm and closing by 11.00 am, with flowers lasting 4-5 days before submerging. Fruits mature underwater, dispersing seeds that are water-mediated, while seedlings produce stolons that develop into rhizomes. Rhizomes segmented and grown under net house conditions showed that intermediate sizes enhanced growth efficiency, with the highest mean leaf number (18.95) and petiole length (24.14 cm) recorded for 0.035 g of rhizome slice. Fragments of rhizome as small as 0.005 g could regenerate fully. Farmers apply systemic herbicides thrice-post-harvest, pre-sowing and post-emergence-eradicating rhizomes, confirming seeds as the primary propagule. Seedling growth under varying water depths revealed that greater depth increased petiole length and leaf area but reduced leaf and flower numbers, with shallow waters producing more flowers. These findings highlight the growth dynamics of *N. rubra* in Kuttanad's paddy ecosystems and the need for sustainable weed management strategies.

Keywords: invasion; Kuttanad; *Nymphaea rubra*; paddy field; rhizome; water lily

Introduction

Kuttanad, situated in Kerala, forms a part of the vast Vembanad kole wetland ecosystem, which gained international recognition as a significant wetland and was designated a Ramsar site in 2002 (1). Vembanad-kole wetland is the largest brackish, humid tropical wetland ecosystem on India's southwest coast, covering 151250 ha, lying 0.6-2.2 m below mean sea level and regularly supporting 20000 residential and migratory waterbirds, along with rich populations of prawns, fish and mangroves. Kuttanad, spanning roughly 55000 ha, covers the districts of Alappuzha, Kottayam and Pathanamthitta. This unique agricultural practice mainly focuses on rice farming, where rice is cultivated after draining the flooded fields known as 'padasekharam' (a term for a group of paddy fields), each covering 200-320 ha. Dubbed the rice bowl of Kerala, this distinctive agro-ecosystem employs a below-sea-level farming system in Kuttanad, which was recognised as a globally important

Agricultural Heritage System (GIAHS) by the Food and Agriculture Organisation (FAO) in 2013 (2). The paddy fields and water bodies in Kuttanad are experiencing a severe invasion of aquatic weeds, driven by nutrient influx and naturally high soil fertility, particularly its organic carbon content as high as 4.33 % as per a study conducted in acid sulphate paddy soils of Kuttanad (3, 4). Recently, these paddy fields have been invaded by the pink-flowered waterlily, *Nymphaea rubra*, especially following the devastating flood that hit the state in 2018 (5). This increase in pink-flowered waterlilies is generating interest in waterlily tourism, akin to that in the Malarikkal region of Kottayam district (Fig. 1) (5). Currently, waterlilies are rapidly spreading across several paddy-growing areas in Kuttanad. The local community holds a positive perception towards the expansion of this species, as it offers additional income during off-seasons (5). However, the environmental impact of this exotic species' invasion remains unaddressed. The rapid proliferation of *N. rubra* in paddy fields is attributed to the high seed

production and vegetative propagation with rhizomes. It is also supported by ecological aspects such as the extensive use of chemical fertilisers in paddy fields, lack of saline water inundation and heavy use of herbicides suppressing other weeds. Understanding the developmental pathways of *N. rubra* from vegetative and seed sources under various conditions is crucial for assessing its ecological impact and management potential. This study examined the effect of varying rhizome sizes on growth parameters of *N. rubra* under net house conditions and the influence of different water depths in inundated paddy fields on growth and flower production in seed-propagated plants.

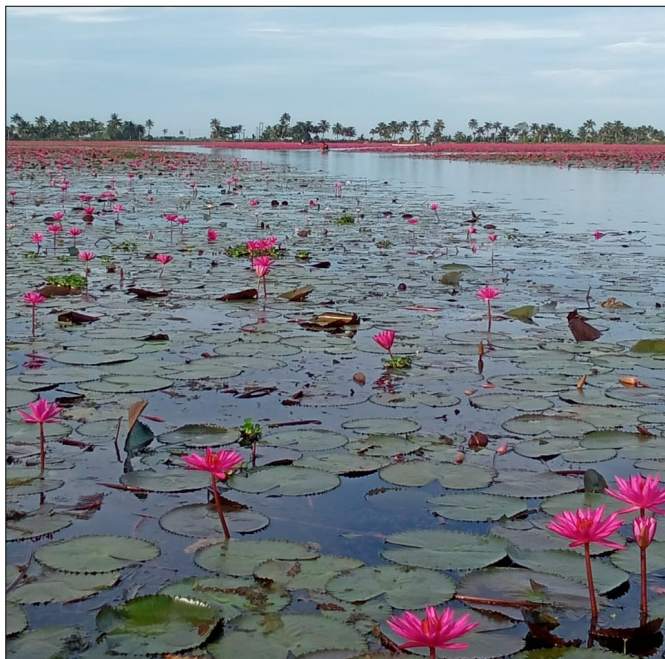


Fig. 1. Field view of pink-flowered *Nymphaea rubra* in Malarikkal area, Kuttanad.

Materials and Methods

The research was conducted in the paddy fields of the Malarikkal area, Thiruvarp Panchayath in the Kuttanad region of Kerala, which is invaded by the pink waterlily *Nymphaea rubra*, located at 9°34'42.9" N latitude and 76°29'29.0" E longitude (Fig. 1). The weed biology was observed to find the flowering behaviour, rhizome formation and seed production in *N. rubra* and the indigenous *N. pubescens*. Ten randomly chosen flowers were tagged at the full bloom stage and the duration of the flowers was observed by monitoring the timing of their opening and closing. The biomass of the waterlily was determined as the average of the fresh and dry weight of samples collected using 1 m² quadrats from 10 locations during the flowering stage.

An experiment was conducted to evaluate the effect of rhizome size on the growth parameters of *N. rubra*. Rhizomes, the vegetative propagules of plants, were collected from the *N. rubra* invaded paddy field and dissected into five horizontal segments of equal length. The sliced pieces were weighed and their diameter was measured using a thread. The size classes recorded were 0.005 g, 5 cm; 0.025 g, 13 cm; 0.035 g, 12 cm; 0.095 g, 20 cm and 70 g, 16 cm weight and diameter, respectively. They were planted in an equal volume of mud in jumbo crates of size 65 × 45 × 31.5 cm under net house conditions. The morphological parameters, including the number of leaves per plant, leaf length and breadth of four leaves per plant, were recorded at weekly intervals for up to 19 weeks. For

each response variable, a one-way analysis of variance (ANOVA) with rhizome size as the factor was fitted using an ordinary least-squares model. Tukeys' HSD test ($\alpha = 0.05$) was used for pairwise comparison among rhizome sizes. Growth rate index (GRI) was calculated as the weekly difference in leaf number (Δ leaves per week) for each size class.

A field study was carried out from June to September 2024 in J block 9000 padasekharam (a cluster of paddy fields) located in the Malarikkal area of Thiruvarp Panchayat in Kottayam district to examine the development of *N. rubra* from seeds, the means of propagation after the flooding of harvested fields. The seedlings emerge one month after flooding and are naturally progressing through various growth stages: seedling, vegetative, flower emergence and full blooming stages. Plant growth was documented across five depth levels: > 2 m, 1.5–2 m, 1–1.5 m, 0.5–1 m and < 0.5 m from June 2024 to the flowering stage in September 2024, using 1 m² quadrat sampling at fixed points marked with poles. Morphological parameters, including, leaf length and width and petiole length of four leaves per m² from each depth and the number of leaves per m² and flower production per m² from each depth were recorded from the same quadrats monthly over four stages (4, 8, 12 and 16 weeks after seedling emergence coinciding with seedling, vegetative, flower emergence and full bloom stages, respectively). In both experiments, leaf area was calculated as the product of leaf length, width and a correction factor of 0.70 (6). All morphological traits of *N. rubra* (petiole length, leaf length, leaf breadth and leaf area) were statistically analysed using a two-way analysis of variance (ANOVA) with water depth and growth stages as fixed factors. Where significant effects were detected, post-hoc comparisons were performed using Tukeys' honest significant difference (HSD) test. All tests were evaluated at $p \leq 0.05$.

Results and Discussion

Weed biology

The flowering behaviour and lifespan of *Nymphaea rubra* were observed in the field conditions of the Malarikkal region. The flowers began to open at 6:00 p.m. and closed by 11:00 a.m., with each bloom lasting between 4 and 5 days (7). The biomass was determined at the flowering stage and found to be approximately 65300 kg ha⁻¹ fresh weight and 5200 kg ha⁻¹ dry weight, similar to the study in water hyacinth recording around 60000 kg of fresh weight, indicating the plants' robust growth and competitive edge over other species (8). Seeds are the main means of propagation in the field, as frequent herbicide applications usually more than three times per season by rice farmers inhibit rhizome growth. Collecting seeds of *N. rubra* from the field was not possible because, after flowering, the pedicel bends, submerging the fruit; seeds mature underwater and are dispersed (Fig. 2). Conversely, seeds of *N. pubescens*, a native species thriving in the area, could be collected as their fruits float on the water surface (Fig. 3). Rhizomes of *N. rubra* took 40–50 days to sprout show the growth of three-week-old *N. rubra* rhizome sprouts and *N. pubescens* seedlings, respectively (Fig. 4 and 5). The rhizomes of *N. rubra* displayed a violet hue beneath the skin (and a violet core in cross-section, aligning with the descriptions in an anatomical study of *Nymphaea* L., species in South India (Fig. 6 and 7) (9). Rhizomes form at the ends of runners or stolons about four months after seedlings emerge (Fig. 8).

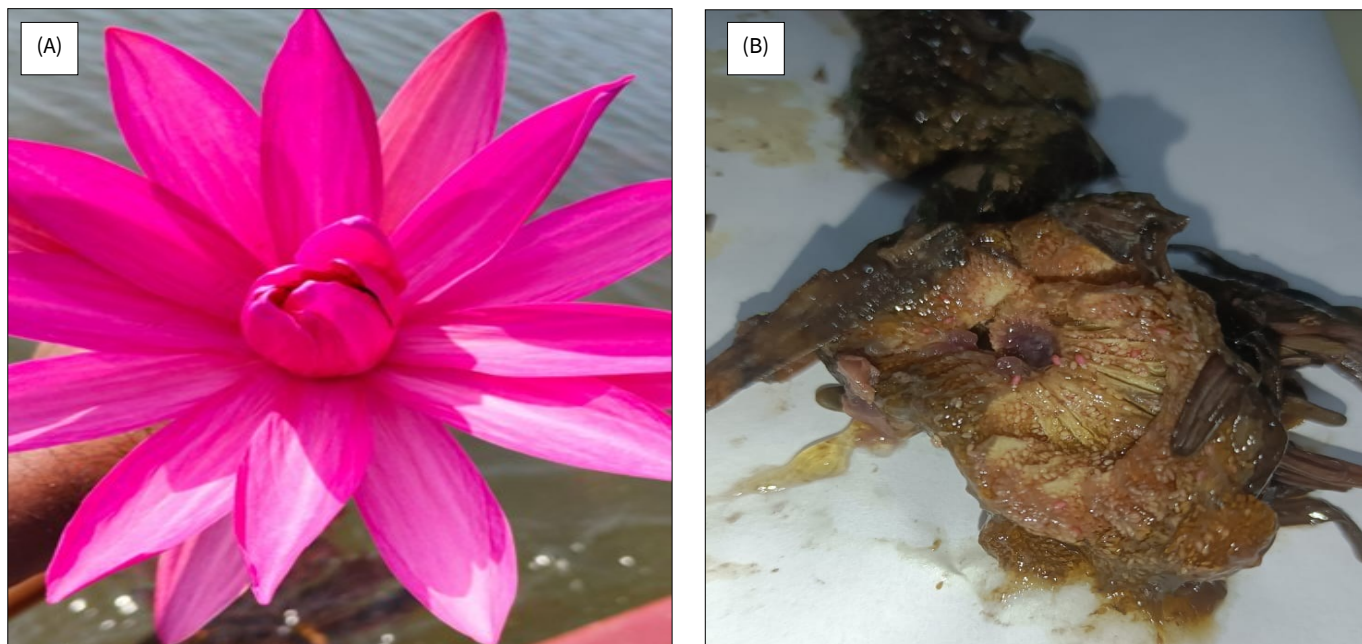


Fig. 2. Flower and immature fruit of *Nymphaea rubra*. (A) Flower; (B) Immature fruit.



Fig. 3. Flower and mature fruit with seeds of *Nymphaea pubescens*. (A) Flower; (B) Mature fruit.



Fig. 4. Three-week-old rhizome sprouts of *Nymphaea rubra*.



Fig. 5. Three-week-old seedlings of *Nymphaea pubescens*.



Fig. 6. Whole rhizome of *Nymphaea rubra*.



Fig. 7. Cross-section of rhizome of *Nymphaea rubra*.



Fig. 8. Rhizome formation in a seedling in *Nymphaea rubra*.

Growth dynamics of *Nymphaea rubra* from vegetative rhizomes and seed propagules

The effect of rhizome size on plant growth in *Nymphaea rubra*

An intermediate rhizome slice (0.035 g; 12 cm) showed the highest leaf production and growth (Fig. 9 and 10). Even very small fragments, as light as 0.005 g, were capable of regenerating and developing into complete plants. This indicates that the rapid spread of *N. rubra* in field conditions is not inhibited by rhizome fragmentation during mechanical tillage with tractors equipped with rotovators, which is commonly practised in dry field conditions after rice harvest.

Impact of water depths on the growth and flowering of *Nymphaea rubra* seedlings

Petiole length, leaf length, breadth and area all showed significant variation across depth and growth stage, which was in line with the findings of a similar study on *Nymphaea odorata* (10). The values of all parameters were consistently highest at > 2 m, with a marked decline below 1.5 m, especially for leaf area. All traits showed an increase from 4 to 16 weeks, with a notable surge between 8 and 12 weeks, indicating a peak in vegetative growth (Table 1, Fig. 11 and 12). The largest leaves and longest petioles were found at depths greater than 2 m, similar to the study in *N. odorata* (Fig. 11 and 12) (10).

Leaf production of *N. rubra* varied markedly across water-depth treatments (Fig. 13). Mean leaf number declined progressively with increasing depth, with the highest values recorded under shallow (< 0.5 m) and shallow-moderate (0.5–1.0 m) water conditions and the lowest values observed at depths exceeding 2.0 m. Temporal patterns indicated rapid leaf production during early growth stages, followed by a gradual decline as plants matured. Depth-mediated variation in leaf production further underscores the vegetative dominance of *N. rubra* under favourable hydrological conditions. High leaf production at shallow and moderate depths, similar to the findings of the study in *N. pubescens*, enhances canopy development, light interception and competitive shading, thereby facilitating rapid occupation of aquatic space (11). Suppression of leaf production at greater depths likely reflects increasing light limitation and energetic costs associated with maintaining elongated petioles. Flower production exhibited a strong depth-dependent response (Fig. 14). Flowering was observed only during later growth stages (12–16 weeks after emergence) and was most pronounced at shallow and shallow-moderate depths. In contrast, plants maintained under deeper water conditions produced few or no flowers. Mean flower number declined sharply beyond 1.5 m water depth, with minimal flowering observed at depths greater than 2.0 m. Flower production was strongly constrained by water depth, with reproductive output largely restricted to shallow and moderately shallow conditions.

Table 1. Leaf length and leaf width of *Nymphaea rubra* under different water depths

Water depth (m)	Mean leaf length (cm)	Mean leaf width (cm)
< 0.5	17.4	15.8
0.5–1	18.5	16.9
1–1.5	19.7	17.8
1.5–2	22.9	21.1
> 2	27.1	25.4
MSE	44.65	43.74
CD (0.05)	4.71	4.66

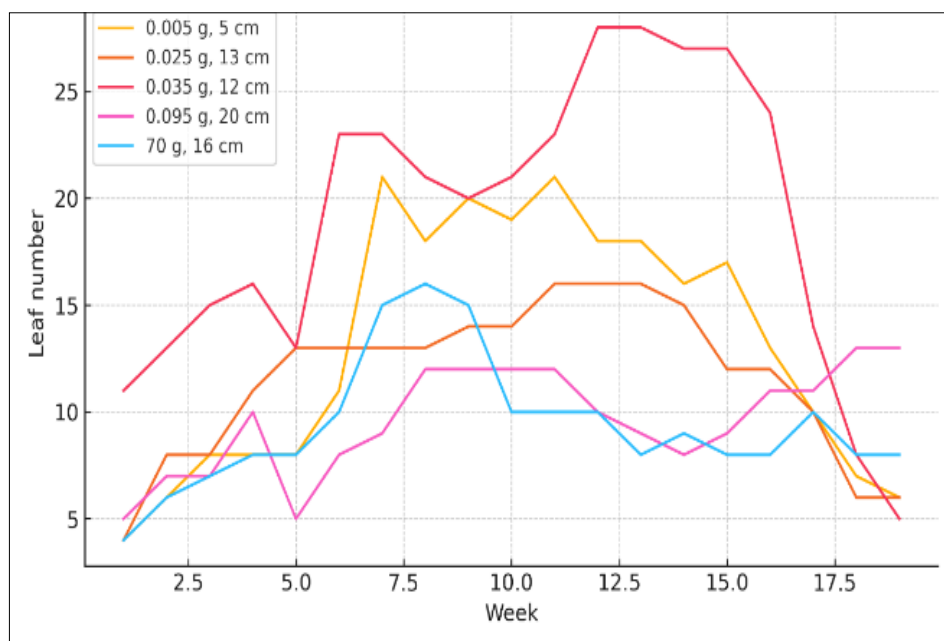


Fig. 9. Effect of rhizome size on leaf number in *Nymphaea rubra*.

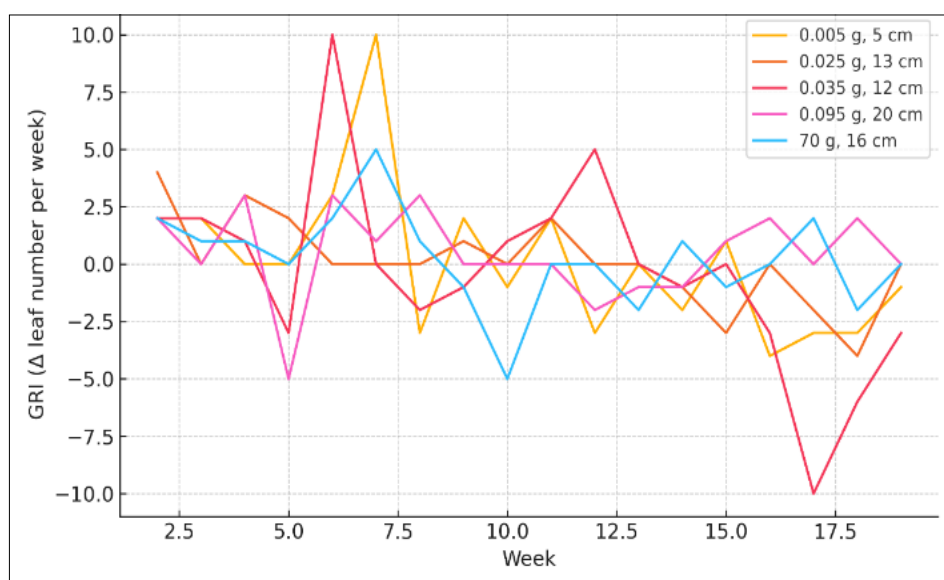


Fig. 10. Effect of rhizome size on growth rate index in *Nymphaea rubra*.

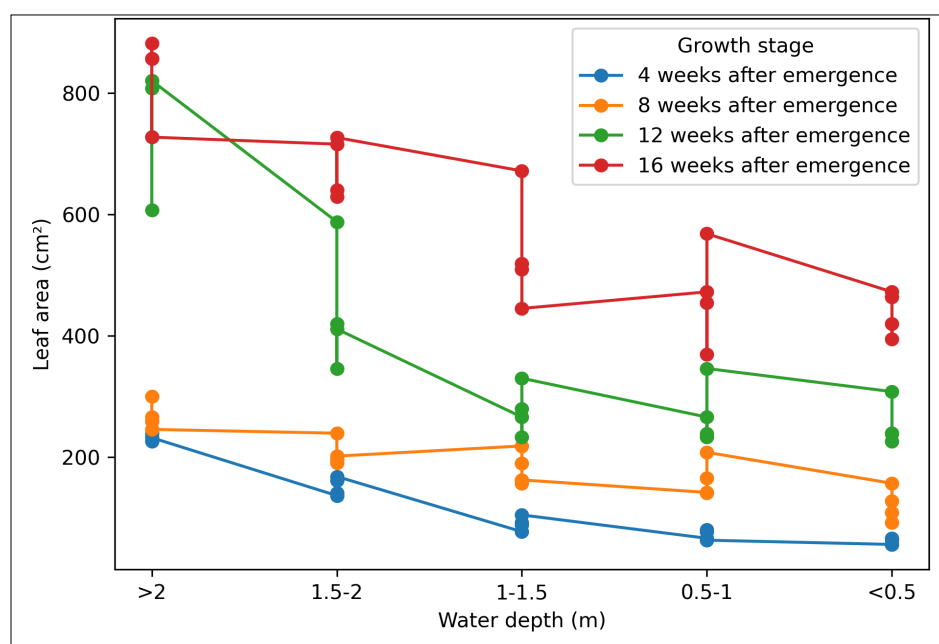


Fig. 11. Effect of water depth on leaf area (cm²) of *Nymphaea rubra*.

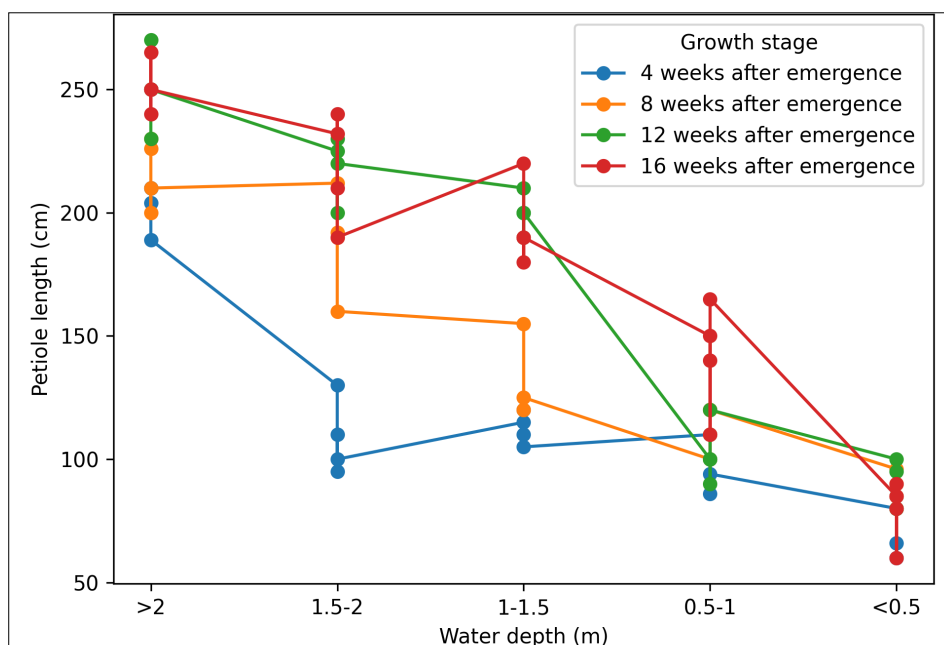


Fig. 12. Effect of water depth on petiole length of *Nymphaea rubra*.

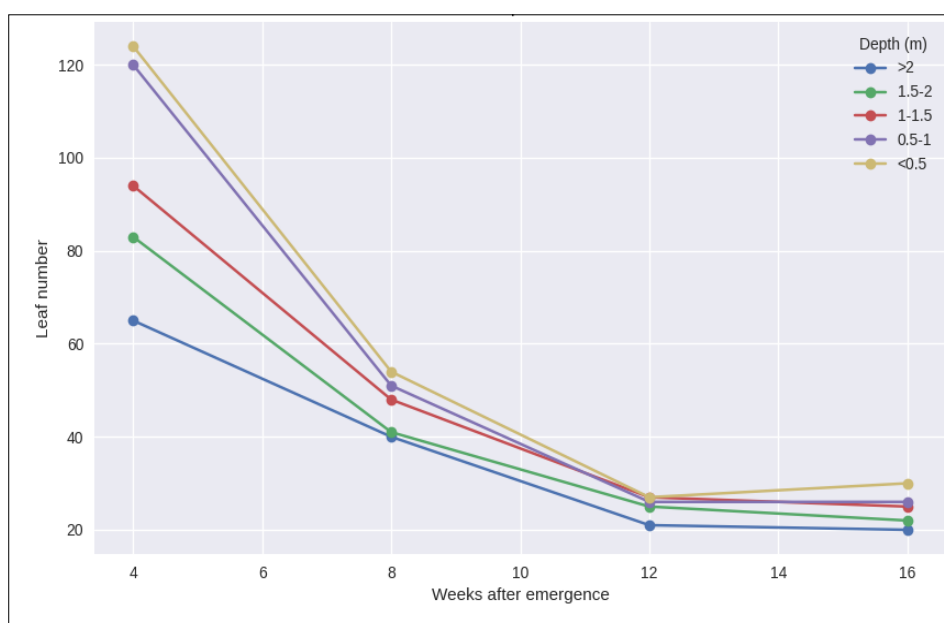


Fig. 13. Effect of water depth on leaf number in *Nymphaea rubra*.

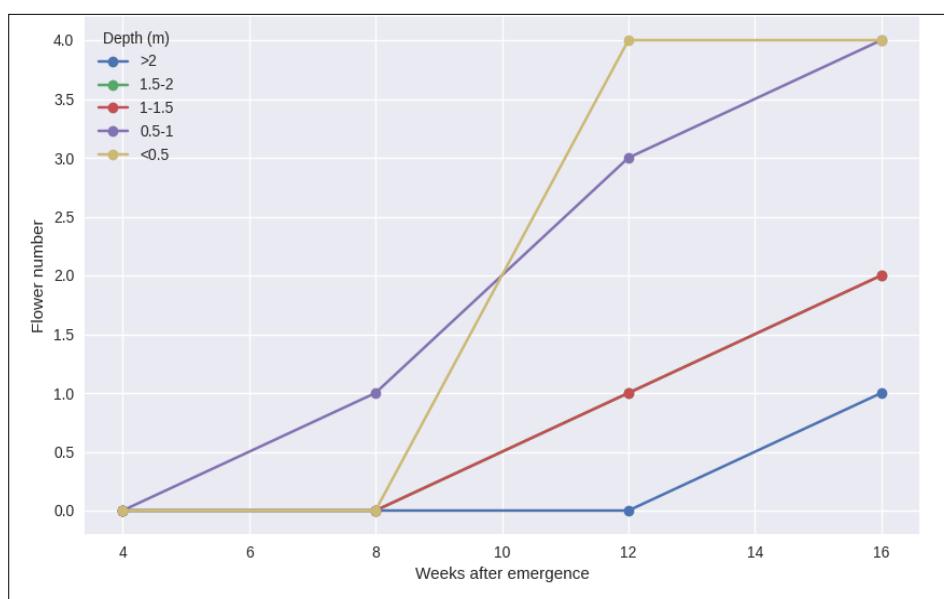


Fig. 14. Effect of water depth on flower production in *Nymphaea rubra*.

Conclusion

The study on weed biology elucidated the floral and rhizome characteristics and quantified the biomass of *Nymphaea rubra*. The substantial biomass production underscores the invasive potential of the species. Seeds were identified as the primary drivers of the rapid proliferation of *N. rubra* in the paddy fields of Kuttanad. Shallow water conditions favoured increased leaf production and flowering, whereas deeper water levels resulted in reduced leaf numbers and limited flowering. Rhizome fragments of medium size exhibited the highest growth efficiency and even minute fragments weighing as little as 0.005 g were capable of regenerating into complete plants, highlighting the efficiency of vegetative propagules for regeneration. These findings clearly demonstrate the adaptive growth behaviour of *N. rubra* in Kuttanad's rice ecosystem and emphasise the urgent need for environmentally sustainable weed management strategies. Integrated weed management strategies, including mechanical incorporation with soil ameliorants such as liming material to accelerate weed biomass decomposition, identifying suitable biological control agents, etc., need to be further investigated. The inundation of saline water during the summer season, coinciding with the opening and closing of the Thanneermukkam saltwater barrage, serves as a natural method for controlling waterlily growth. Therefore, the timely operation of the barrage offers a natural solution for managing all aquatic invasive weeds in the ecosystem, including the invasive pink waterlily, *N. rubra*.

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Authors' contributions

DVS, the Principal Investigator of the project, conducted the study. NJ provided guidance for the execution of the research. SS assisted in the field experiments and laboratory analyses. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Paperpal in order to paraphrase the text. Copilot was used for doing the statistical analysis and preparing charts for the research data. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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