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The driving effect of water immersion on *Pomacea canaliculata* eggs

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Abstract

Pomacea canaliculata poses a significant threat to agricultural wetlands, yet chemical control measures raise environmental concerns. This study aims to evaluate timed water submersion as a non-chemical strategy for suppressing egg hatching of this invasive species. Controlled inundation was tested as a non-chemical strategy to suppress egg hatching of the invasive *P. canaliculata*, and egg abundance was estimated using morphometric egg-mass parameters under laboratory conditions. Short-term immersion (1–2 days) produced no significant reduction in hatching rate, while immersion for 4–5 days significantly delayed embryonic development and reduced final hatching success. Complete hatching failure was observed for eggs subjected to continuous five-day submersion under standardized laboratory settings. Visual observations of 10-day prolonged flooding, which triggered extensive egg detachment and embryonic necrosis, were only auxiliary qualitative recordings and were not included in the formal quantitative hatching trial spanning 0–5 immersion days. Morphometric analysis confirmed a significantly positive linear correlation between egg number and egg-mass longitudinal length ($p < 0.05$), enabling non-destructive egg-quantity prediction based on egg-mass length. Our results confirm that timed water submersion serves as an eco-friendly alternative for controlling golden apple snail proliferation, yet further field validations are required before large-scale agricultural application.

Keywords: Driving effect; Pomacea canaliculate; Water immersion; Hatching rate; Hatching time

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1. Introduction

Pomacea canaliculata (synonymously *Ampullaria canaliculata*)[1], commonly known as the golden apple snail, is a freshwater gastropod mollusk taxonomically classified within the family Ampullariidae, order Architaenioglossa. This species, indigenous to the Amazon River Basin in South America, was intentionally introduced to Guangdong province, China, during the 1980s due to its nutritional value as a high-protein food source for human consumption.[2]

Pomacea canaliculata exhibits remarkable ecological adaptability, which is reflected in several key biological traits: (i) As an amphibious species, it possesses both branchial and pulmonary respiration, enabling short-term aerial survival in addition to aquatic

habitation; (ii) it demonstrates considerable thermal tolerance, with an optimal growth temperature range of 25–32 °C, an upper critical threshold of 45 °C, and a lower survival limit of 5 °C; (iii) its euryphagous diet encompasses a wide variety of plant matter (e.g., rice, *Azolla*, *Eichhornia crassipes*, and *Lemna minor*) as well as detrital and animal-derived nutrients (e.g., wheat bran, corn flour, fish meal, eggshells, and shrimp); and (iv) it exhibits high fecundity, with an average lifetime egg production of 13,764 per female, 1–3 annual generations, and overlapping generational cohorts.[3]

Pomacea canaliculata is a predominantly herbivorous species, with rice (*Oryza sativa*) as its primary crop host, where infestation can lead to yield losses ranging from 10% to 90%.[4] Due to its high competitive capacity, this invasive gastropod exerts significant ecological pressure on native snail populations, contributing to reduced biodiversity within invaded ecosystems. Beyond its impact on indigenous mollusks, *P. canaliculata* also negatively influences other aquatic organisms; its rapid proliferation, substantial feeding rates, and broad dietary spectrum have been associated with measurable declines in fish and shellfish populations, disrupting local aquatic food webs.[5,6]

The management of *P. canaliculata* egg masses has emerged as a critical agricultural challenge, primarily due to the species' exceptionally high reproductive capacity and its demonstrated potential to inflict substantial damage to economically important crops, particularly rice.[7–9] This invasive pest has rapidly expanded its range across multiple geographic regions, establishing itself as a significant threat to global food security and sustainable agricultural practices. Among the diverse control strategies currently employed, water immersion has gained recognition as both an ecologically sustainable and operationally feasible intervention method.[10]

The application of water immersion as a biological control measure has become particularly prevalent in endemic regions affected by *P. canaliculata* infestations, with empirical field observations confirming substantial reductions in snail population densities following implementation. However, the efficacy of this methodology demonstrates significant dependence on multiple interacting variables, including but not limited to hydroperiod duration, ambient water temperature regimes, and precise temporal synchronization with the target organism's reproductive chronology.[11]

Contemporary research efforts have extensively investigated the environmental resilience of *P. canaliculata* developmental stages, with particular emphasis on embryonic tolerance thresholds to various abiotic stressors, including desiccation, nutritional deprivation, hydrostatic pressure, and chemical exposure. Given the technical feasibility of hydrological regulation in agricultural ecosystems through engineered water management systems, the flood resistance characteristics of *P. canaliculata* ova have become a focal point of applied ecological research. Critical findings indicate that embryonic viability is significantly compromised when egg masses experience continuous submersion exceeding 48 h during the initial 12-h post-oviposition period, manifesting as both reduced eclosion rates and prolonged developmental durations. Furthermore, diurnal cycling of immersion (daytime flooding coupled with nocturnal drainage) has been shown to disrupt normal embryogenesis, with treatment efficacy being inversely proportional to embryonic age—maximal impact occurring when interventions are initiated before the four-day developmental milestone.[12]

Water immersion represents a biologically targeted and operationally scalable control strategy for *P. canaliculata* egg masses, whose widespread adoption in agricultural practice reflects both its practical implementation advantages and measurable population suppression outcomes, ultimately contributing to enhanced crop protection and yield preservation.[13] This study employed controlled laboratory experiments to systematically assess differential hatching responses in newly oviposited *P. canaliculata* egg masses under varying water-immersion durations (0–5 days), with the overarching objective of establishing empirical evidence for water-level manipulation as a viable population control mechanism.[14] Water immersion as a control measure is widespread in areas where *P. canaliculata* is a problem. Farmers have reported significant reductions in snail populations after implementing this technique. However, it is important to note that the success of water immersion depends on several factors, including the duration of flooding, water temperature, and the timing of immersion relative to the egg-laying cycle of the snails.

2. Materials and methods

2.1. Experimental materials

Newly oviposited egg masses of *P. canaliculata* were collected on August 5, 2024, from the littoral wetland ecosystem of Yilong Lake (23°28'–23°29' N, 102°28'–102°38' E), a shallow plateau lake located in Yunnan, China. This lacustrine system, situated at an elevation of 1,414.2 m above sea level, encompasses a surface area of 30 km^2 within a catchment basin of 360.43 km^2, with an average depth of 2.75 m and a total water storage capacity of 1.149×10^8 m^3.

The sampled egg masses exhibited characteristic morphological features of early developmental stages: bright reddish coloration, loosely adhesive attachment

to submerged vegetation, and surface encapsulation by a viscous mucoprotein matrix. To preserve structural integrity during transport, egg-bearing stems were carefully excised and secured in aerated containers using non-reactive adhesive tape, followed by immediate transfer to a climate-controlled greenhouse facility in Kunming. Environmental parameters within the greenhouse were maintained at ambient light penetration (12:12 h light–dark cycle) and passive ventilation to simulate natural riparian conditions (Figure 1). Invertebrate experiments do not require approval by an ethics committee.

These control egg masses were maintained under identical ambient laboratory conditions (temperature, humidity, light) as the treatment groups, but were exposed only to atmospheric air without any immersion for the entire duration until assessment.

2.2. Experimental design

2.2.1. Quantitative morphometric analysis of egg mass granule

To establish a predictive model for estimating embryonic unit counts within irregularly shaped *P. canaliculata* egg masses, a morphometric protocol was implemented (Figure 2). Three-dimensional parameters were operationally defined as follows:

(i) Length: Linear distance between terminal points along the longitudinal axis of stem attachment.
(ii) Width: Maximum orthogonal dimension perpendicular to the longitudinal axis.
(iii) Height: Vertical extent from substrate to apex under standardized horizontal stem orientation.

A stratified random sampling approach was employed to select egg masses spanning a size continuum. Morphological measurements were acquired using digital vernier calipers (resolution: 0.01 mm), followed by manual disarticulation of individual egg granules under stereomicroscopic guidance. Pearson correlation coefficients were subsequently used to correlate dimensional parameters (e.g., length, width, height) with absolute granule counts, enabling non-destructive estimation of embryonic populations for subsequent immersion trials.

2.2.2. Hydrological stress protocol for embryonic development

(a) Experimental cohorts

Egg masses collected in situ were partitioned into six treatment groups (n = 5 biological replicates per group) through stratified randomization:

(i) Control cohort (0 d): Maintained under atmospheric exposure without immersion.
(ii) Experimental cohorts: Subjected to controlled immersion durations of 1–5 days post-collection.

(b) Immersion methodology

To simulate natural hydroperiod fluctuations while preventing buoyancy artifacts, egg-bearing stems were affixed to glass rods using non-reactive polymer tape, ensuring complete submersion in aerated aquatic microcosms (25 ± 1 °C, pH 7.2–7.6). Upon termination

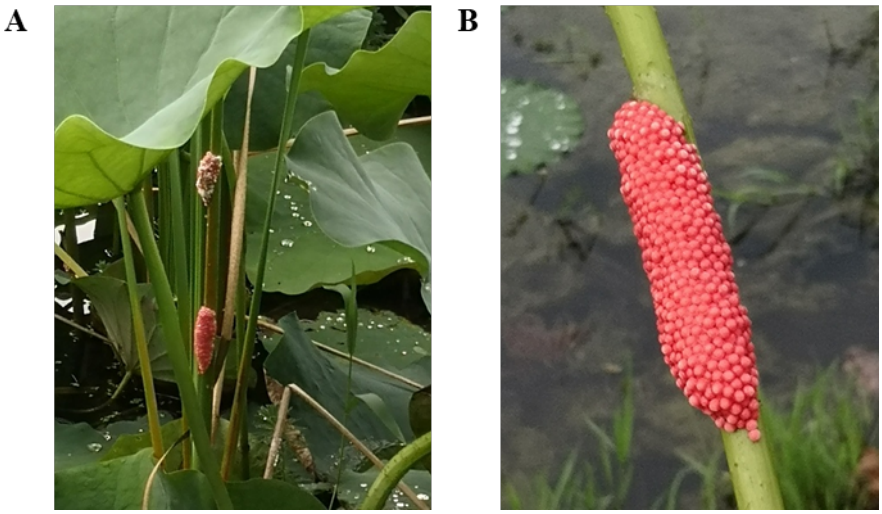

Figure 1. Experimental materials. (A) The eggs are attached to the lotus stem. (B) The attachment characteristics of the eggs.

of designated immersion intervals, water levels were systematically reduced to establish a 2–5 cm air–water interface, replicating transitional wetland conditions during seasonal drawdown phases.

(c) Developmental monitoring

Quantitative assessments of eclosion dynamics were conducted through diurnal observational cycles (08:00–18:00 local time) with concurrent logging of abiotic parameters: ambient temperature (Δ ± 0.5 °C), relative humidity (Δ ± 3%), and photosynthetically active radiation ($\mu mol \cdot m^{-2} \cdot s^{-1}$). Neonatal snails were enumerated via a standardized protocol:

(i) Mechanical dislodgement of hatchlings from substrates using soft-bristle brushes.

(ii) Systematic transfer of individuals through serial water aliquots (200 mL) in graduated cylinders.

(iii) Photographic enumeration under dark-field illumination to enhance contrast.

Post-enumeration, experimental vessels were replenished with dechlorinated water (24 h-aerated municipal supply) to maintain constant hydrochemical conditions. Eclosion rates were calculated as the cumulative number of neonates per egg mass, normalized to initial granule estimates from Section 2.2.1.

2.3. Analyzing method

2.3.1. Correlation analysis of morphometric parameters

Statistical analyses were performed using SPSS software (v.28, IBM Corp., United States) to assess linear correlations between triaxial morphometric parameters (e.g., length, width, height) and embryonic counts within *P. canaliculata* egg masses. Pearson correlation coefficients were calculated to identify parameters associated with granule numbers. A p-value < 0.05 was considered statistically significant.

2.3.2 Cumulative eclosion rate calculation

Embryonic viability was evaluated as cumulative eclosion rates, defined by the ratio of total neonates observed between August 5 and September 2, 2024. Daily neonate enumerations were aggregated across the 29-day observation period to compute final viability metrics.

3. Results and discussion

3.1. Morphological parameters of egg masses

Quantitative characterization of *P. canaliculata* egg masses was performed through systematic measurement of triaxial dimensions (length, width, height) and the number of eggs. Correlation analyses revealed statistically significant univariate associations between morphometric parameters and reproductive output. A strong positive correlation was identified between length and the number of eggs (r = 0.8183, p = 0.0011), as well as egg numbers and length × width (r = 0.7417, p = 0.0058). Conversely, no statistically significant correlations were detected between egg numbers and either transverse width, vertical height, or higher-order interaction terms encompassing length × height, width × height, and length × width × height (all $p \geq 0.05$; Table 1 and Figure 3). These findings demonstrate that the number of eggs is predominantly explained by longitudinal egg mass extension, with lateral and vertical dimensions exhibiting negligible influence.

The heatmap analysis (Figure 4) revealed a statistically significant positive correlation between the number of eggs and length ($p < 0.05$), whereas width and height exhibited no significant association with egg number ($p \geq 0.05$). Furthermore, the correlation between width and height was statistically insignificant ($p \geq 0.05$).

A significant positive correlation was observed between egg mass length and egg number (r = 0.818, p = 0.001) in *P. canaliculata*. This morphological correlation may be attributed to oviposition behavior, in which eggs are deposited unilaterally along plant stems, with the primary

Figure 2. Egg immersion experiment. (A) Current status of incubation. (B) Eggs enumeration. (C) Measurement of egg masses.

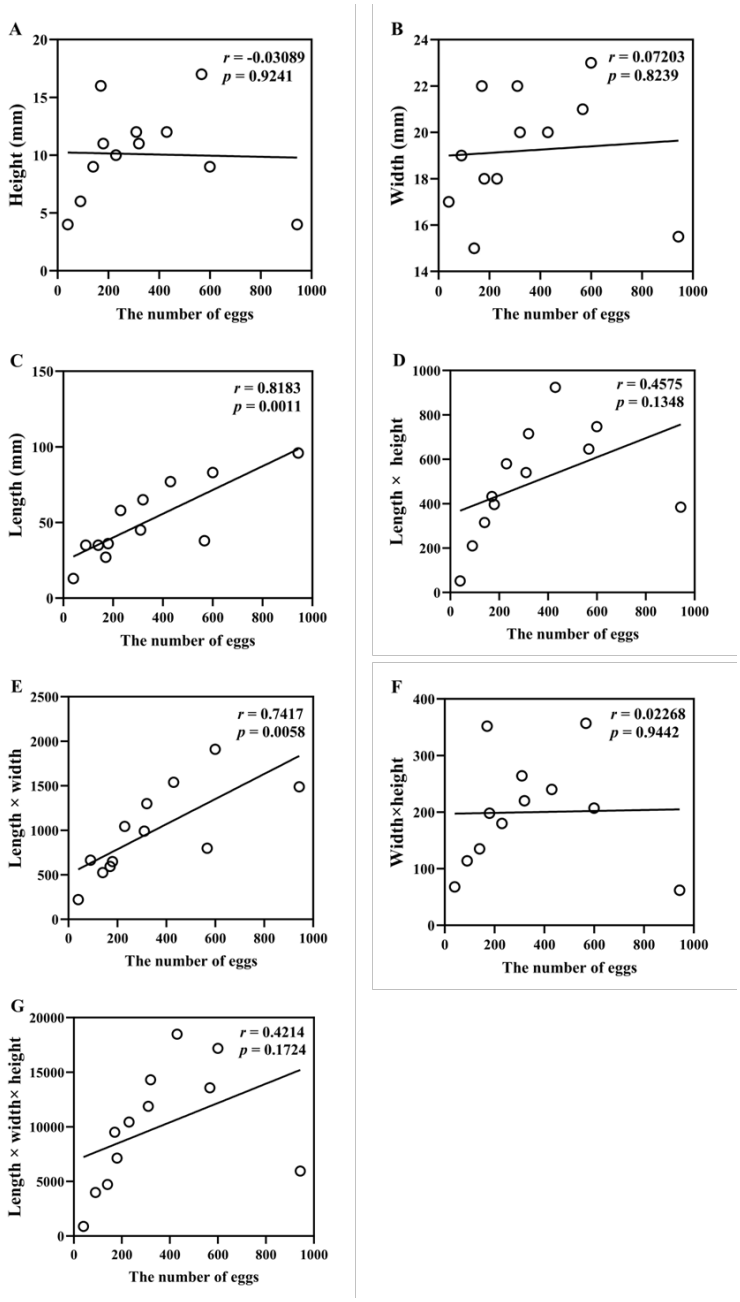

Figure 3. Correlation analysis between the number of eggs and morphological parameters. (A) Correlations between number of eggs and (A) height, (B) width, (C) Relationship between length, (D) length × height, (E) length × width, (F) width × height, or (G) length × width × height.

Table 1. Correlation analysis between the number of eggs and morphological parameters

Number of eggs	Length	Width	Height	Length × width	Length × height	Width × height	Length × width × height
Pearson correlation coefficient (r)	0.818**	0.072	−0.031	0.742**	0.458	0.023	0.421
p-value	0.001	0.824	0.924	0.006	0.135	0.944	0.172

Note: **$p < 0.01$ indicates a horizontally (bilaterally) significant correlation.

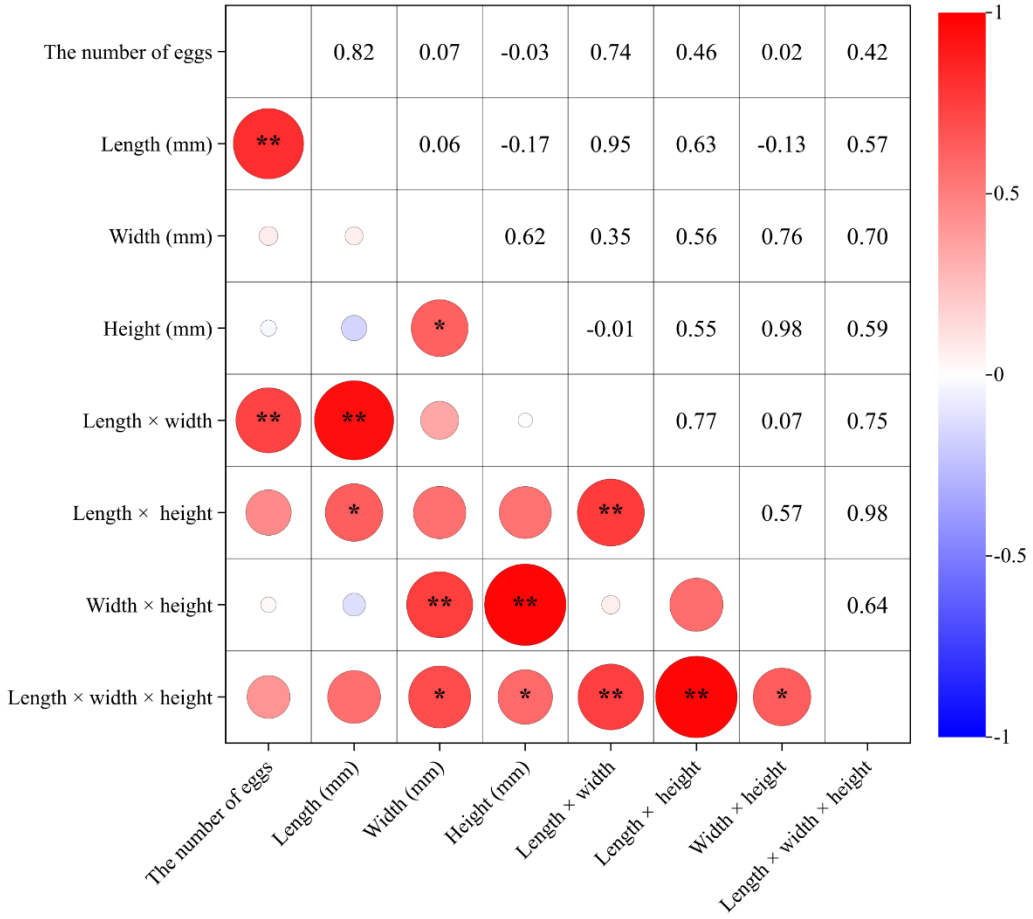

Figure 4. Heatmap analysis of the number of eggs and morphological parameters

axis of egg mass elongation being determined by stem contact geometry. The exclusive association between egg mass length and egg number indicates that selective pressures have favored a unidimensional growth strategy over volumetric expansion.

Primary morphological constraints on egg mass shape are imposed by the spatial limitations of the oviposition site. In wetland ecosystems, *P. canaliculata* selectively deposits eggs on emergent macrophytes characterized by slender, elongated stems that provide substantially greater axial than lateral spatial accommodation. An adaptive reproductive strategy is hypothesized to have evolved, in which resources are preferentially allocated to longitudinal egg mass extension rather than radial expansion.

This optimization achieves maximal fecundity at minimal energetic cost by efficiently utilizing the predominant vertical dimension of stem substrates and by reducing structural material requirements per unit egg volume. The phyllotaxis of emergent vegetation creates a critical microhabitat that maintains >95% relative humidity—essential for embryonic development—while preventing lethal submergence through stem angulation. This geometric configuration is exploited through axial egg mass elongation, which simultaneously minimizes dehydration risk by maximizing contact with the humid stem surface and reduces the probability of hydrostatic immersion by elevating the eggs above the waterline.[15]

In static aquatic environments such as paddy fields, where hydrodynamic disturbances are minimal, egg mass attachment is primarily influenced by gravitational forces, wind action, and biological collisions, with limited contribution from width/height dimensions to overall adhesion strength. Optimal substrate utilization is achieved through unilateral linear attachment (as opposed to circumferential wrapping) along stem surfaces. The stem diameters of emergent macrophytes (e.g., rice; 5–8

mm) fall precisely within the ideal attachment range for *P. canaliculata* egg masses (5–15 mm), enabling firm conformal contact that significantly reduces dislodgment risk. Under these static conditions, a positive correlation was observed between egg mass length and attachment stability, with longer egg masses demonstrating 40% lower detachment rates compared to shorter variants ($p < 0.05$). This attachment mechanism exhibits pronounced morpho-functional adaptation, in which elongated egg-mass geometry confers superior environmental fitness.[16]

The oviposition strategy of *P. canaliculata* egg masses has been demonstrated to represent a profound adaptation to amphibious environments, a trait considered crucial to its global invasive success. This biological characteristic has been identified as a key target for the development of effective control measures.

3.2. Hatching rate and hatching time

3.2.1. Appearance of egg masses following water immersion

The appearance of egg masses under water-immersion control is shown in Figure 5 and Table 2. After 1–3 days of immersion, egg masses exhibited a chromatic transition from bright red to pale red or grayish white, as quantified by spectrophotometry. Minimal oocyte lysis (<10% of total eggs) was recorded, while the overall adhesive integrity of the egg masses was maintained.

After five days of immersion, the majority of egg masses were observed to undergo chromatic transition to pale pink or grayish-white coloration. Partial oocyte rupture was initiated, while the egg masses remained firmly attached to the stem substrates.

Following 10 days of continuous immersion, a complete chromatic transition of all egg masses to pale pink or grayish-white coloration was observed. Extensive oocyte rupture and tissue decomposition were documented, accompanied by a significant increase in egg mass detachment rates.

The egg masses of *P. canaliculata* contain a specialized hemoglobin synthesized by the embryonic para-branchial gland. The heme-bound ferrous iron (Fe^{2+}) in this respiratory pigment has been demonstrated to form oxygenated complexes that exhibit bright red coloration, analogous to the chromogenic mechanism observed in vertebrate hemoglobin.[17] The chromatic transition of egg masses is attributed to oxidative degradation of hemoglobin. Bright red coloration is indicative of normally oxygenated hemoglobin, suggesting proper embryonic development. Under hypoxic conditions, ferrous iron (Fe^{2+}) is oxidized to ferric iron (Fe^{3+}), inhibiting hemoglobin metabolism and leading to cellular viability loss.[18]

The chromatic transition of egg masses serves as a visual indicator of developmental arrest. This colorimetric response has been identified as a physiological stress marker reflecting embryonic hypoxia adaptation during immersion, thereby providing a biochemical basis for non-destructive field assessment of egg viability.

3.2.2. Hatching rate and hatching time

Water immersion has been demonstrated to be an effective method for controlling the hatching of *P. canaliculata*. In this study, the effects of immersion duration on the hatching rate and hatching time of *P. canaliculata* were investigated.

The immersion duration for egg masses was systematically established at six intervals (0, 1, 2, 3, 4, and 5 days), with five replicates per treatment duration. For each immersion time point, the mean hatching rate and mean hatching time were calculated across all five biological replicates (Figure 6 and Table 3).

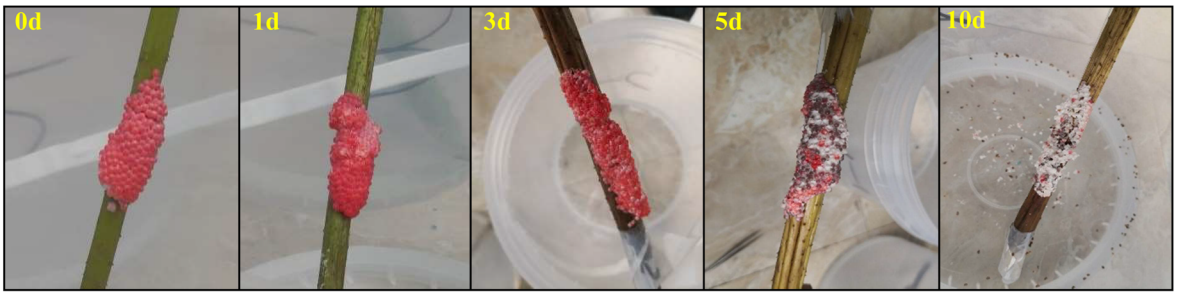

Figure 5. The appearance of egg masses under water-immersion control

Table 2. Effects of immersion duration on *Pomacea canaliculata* egg mass viability

Immersion duration	Chromatic alteration	Oocyte rupture degree	Adhesive performance
0 day (Control)	Bright red	Intact (100% viability)	Strong (detachment rate < 5%)
1 day	Bright red → Pale red/Grayish white	Minor (5%)	Strong (detachment rate < 5%)
3 days	Bright red → Pale red/Grayish white	Partial (10 ± 5%)	Moderate (detachment rate 5–10%)
5 days	Pale red → Grayish white (>80%)	Partial rupture (30 ± 5%)	Intermediate (detachment rate 15–20%)
10 days	Uniformly pale pink/Grayish white	Extensive rupture (>95%)	Weak (detachment rate 80–90%)

The non-immersed control group (0d) exhibited initial hatching on Day 11, with clustered hatching observed between Day 17 and Day 23 (Figure 7). The final hatching event was recorded on Day 25. The non-immersed control group demonstrated the earliest hatching initiation and the longest recorded hatching duration among all experimental conditions. The total hatching success rate was 64.15%.

The 1-day and 2-day immersion group (1d and 2d) exhibited consistent hatching patterns (Figure 7). The initial hatching was observed on Day 18, with the clustered hatching phase occurring on Days 18–22. The final hatching was recorded on Days 27–29. Compared with non-immersed controls, hatching initiation was delayed by 6–7 days, while the duration of mass hatching remained consistent. The final hatching time was extended by 2–4 days. The total hatching rates were calculated at 37.58% and 30.97%, respectively.

The 3-day immersion group (3d) exhibited significantly delayed hatching characteristics (Figure 7). The initial hatching was observed on Day 21, with the clustered hatching phase occurring on Days 21–28. The final hatching was recorded on Day 29. The total hatching rate was calculated as 31.28%.

The 4-day immersion group (4d) observed a significant hatching delay. The initial hatching occurrences were recorded on Days 27–29. Among the five replicates, viable hatchlings were detected in three. More strikingly, the 5-day immersion group (5d) recorded no successful hatching. The total hatching rates were 3.04% and 0% for the 4d and 5d groups, respectively (Figure 7).

A significant delay in hatching initiation was consistently observed in both the 1-day and 2-day immersion groups. Moderate reductions in hatching rates were also observed, though the biological significance of these decreases remains to be quantified. Immersion durations of 4–5 days were demonstrated to achieve population-level control, with substantial reductions in hatching success (≥90%) and in viable offspring production documented. Wang *et al.*[4] reported that eggs submerged in water for four days, beginning within 0–6 h, could easily decrease hatchling rates to 20–30%. Their study also showed that water spraying and submersion could dramatically decrease the hatchling rate to 5.8% and increase the hatchling duration up to 26.4 days on *P. canaliculata*.

Table 3. Mean and standard deviation of hatching rate

Immersion day	Mean hatching rate (%)	Standard deviation
0d	64.15	24.71
1d	37.58	26.46
2d	30.97	41.24
3d	31.28	19.64
4d	3.04	5.14
5d	0.00	0.00

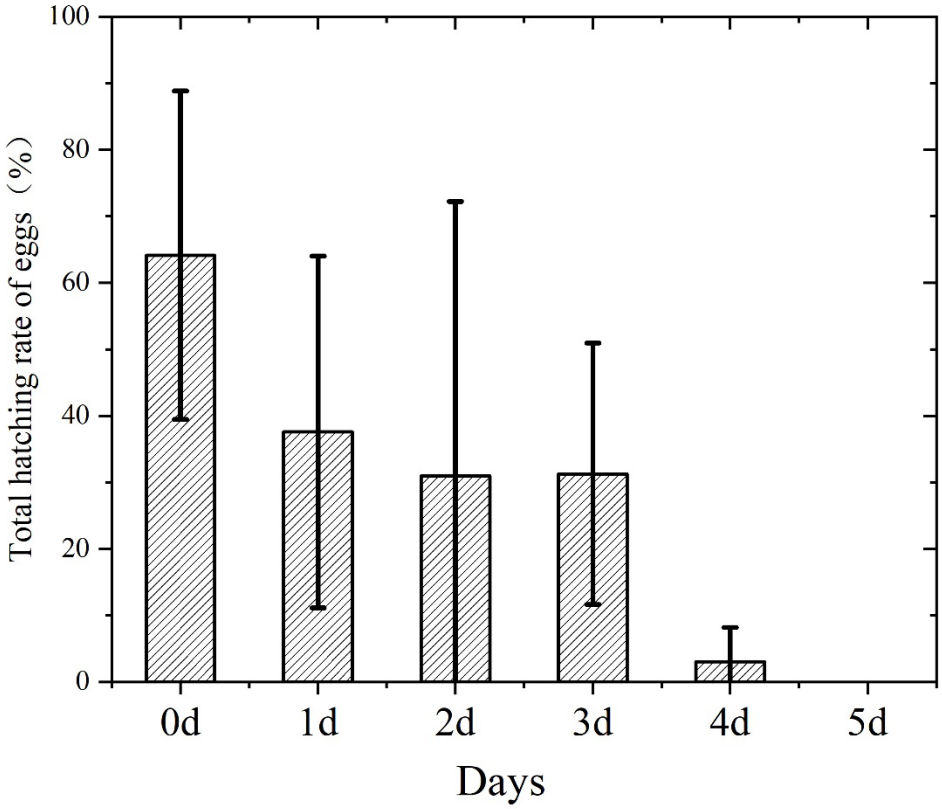

Figure 6. The total hatching rate of eggs with different water-immersion conditions

It was reported that embryonic growth of *P. canaliculata* is greatly inhibited by water condensation on the eggs, and repetitive wetting of the eggs affects hatchling and development negatively.[19] Therefore, the flooding conditions played an important role in the lethal impact on *P. canaliculata*. *P. canaliculata* is more likely to survive if the water is drained or lost. In their experiments, *P. canaliculata* mortality was greater in flooded conditions for several days.[20,21]

Significant variations in hatching performance were observed among egg masses within the same treatment group. Under identical submersion durations, differences were recorded in three key parameters: initial hatching time, clustered hatching timing, and total hatching rate among different samples. These variations were attributed to potential individual differences among parent snails, which were found to influence both the hatching process and outcomes.

Within individual egg masses, a distinct "clustered hatching" pattern was demonstrated. This phenomenon was characterized by 1–2 concentrated hatching events during the incubation period, during which significantly fewer hatchlings were observed at other times. The clustered hatching phase was determined to last 5–6 days. The proportion of hatchlings emerging during this clustered period exceeded 70% of total hatchlings in most egg masses, with a maximum of 96%. The initial hatching date closely approximated the clustered hatching date, typically differing by 0–2 days. Huang *et al.*[22] reported that short-term hypoxia triggered a metabolic suppression state in eggs, reducing oxygen consumption to prolong survival without immediate lethality, with gas exchange restoration occurring after egg mass desiccation. Prolonged hypoxia exceeding 48 h was demonstrated to lead to energy depletion and cellular damage in egg masses. The developmental process of the spare embryo was terminated by hydrolysis of the calcified eggshell layer ($CaCO_3$), impairing oxygen

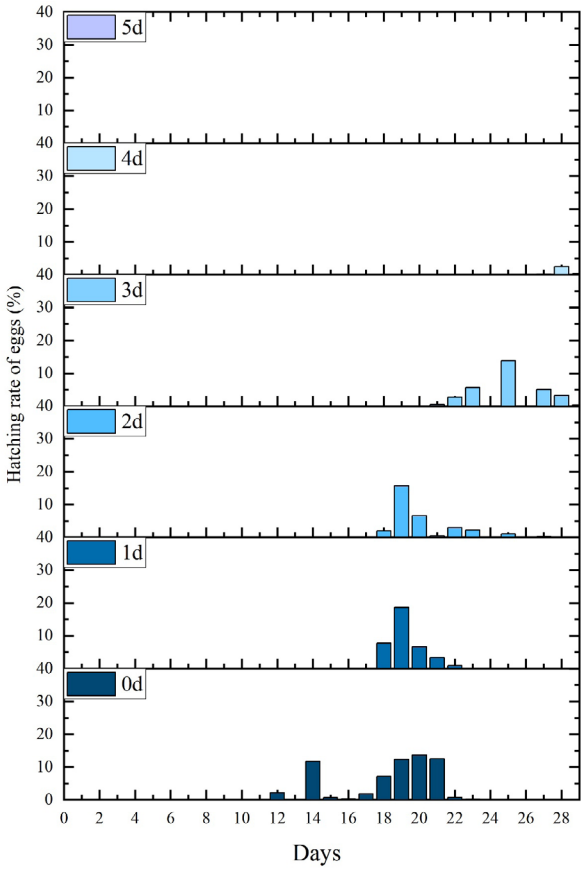

Figure 7. The hatching rate of eggs with different water-immersion conditions

exchange, accelerating microbial colonization, and promoting egg mass decomposition.[10]

Pomecea canaliculata continues to be recognized as a significant biotic constraint in rice cultivation systems, with substantial yield losses reported across multiple agroecological regions.[23,24] It has been empirically demonstrated that no individual control strategy can be considered fully efficacious in preventing snail-induced damage to rice crops.[25]

Multiple cultural control practices should be implemented, including water management strategies to reduce the mobility of snails. During the peak oviposition period of *P. canaliculata* (e.g., when temperatures exceed 25 °C), water levels can first be lowered to induce egg deposition, followed by controlled flooding to submerge and destroy egg masses, thereby achieving efficient population control.[26,27]

This experiment focuses on the egg masses of *P. canaliculata*, but prolonged immersion may similarly affect the eggs of native snails and the early life stages of certain aquatic insects (such as Ephemeroptera and Odonata). In practical application, it is recommended to integrate local biodiversity surveys, selectively implement inundation during periods with minimal impact on non-target organisms (e.g., avoiding their peak reproductive seasons), or adopt localized and rotational flooding strategies to mitigate ecological risks.

Current cultural control measures are predominantly focused on damage mitigation rather than direct reduction of snail population densities. Post-harvest flooding with a water depth sufficient to submerge egg masses for ≥5 days significantly inhibits *P. canaliculata* reproduction by preventing egg hatching.[28] In agricultural water conservancy construction, the slope gradients of ditches along with water storage and drainage capacities should be optimized to ensure periodic submergence of areas susceptible to egg mass attachment.[29]

This method is most applicable to areas with controllable water sources (such as irrigation canals or paddy fields with adjustable water levels), particularly when implemented before rice transplantation or during fallow periods, as it can be integrated into existing water management practices.

The water immersion technique achieves suppression of *P. canaliculata* populations with minimal environmental impact, serving as a critical component of agricultural green prevention and control systems. Future optimization should integrate biological synergists and smart farming technologies to enhance applicability.

The present findings should be understood not only as an assessment of the effects of controlled water immersion on *P. canaliculata* egg hatching but also as a contribution to the broader development of sustainable pest-control strategies. As a water-immersion technique for *P. canaliculata* egg masses, it can be seen as an environmentally friendly method that complements other sustainable agricultural practices. However, it should be noted that this method cannot be used independently. The implementation of water immersion in field practice will require combining it with water-level regulation, crop rotation, and other agrotechnical measures. Such an approach is consistent with recent works demonstrating that sustainable agricultural systems can be reinforced by integrating biological, mechanical, and agrotechnical approaches into a coherent management strategy. In this case, water immersion of *P. canaliculata* egg masses may serve as one element of the overall crop protection strategy in irrigated and paddy fields. Still, it should be recognized that the present study focuses on demonstrating specific effects on eggs under laboratory-controlled conditions and cannot serve as direct evidence for large-scale universal agricultural practices.

Water submersion delivers lower environmental risks than chemical molluscicides, yet long-term full-field flooding may negatively affect native freshwater snails and immature aquatic insects such as Ephemeroptera and Odonata larvae. To mitigate damage to non-target organisms, practical field implementation requires staggered, intermittent flooding outside the peak reproductive period of local native aquatic biota. All suggestions for optimizing farmland ditch slope and irrigation drainage design are restricted as preliminary proposals; field verification is essential before incorporating submersion technology into formal agricultural water conservancy planning.

4. Conclusion

We found that the number of *P. canaliculata* eggs is significantly correlated with egg mass length, indicating that egg number increases primarily with body length, while width and height have minimal influence. This exclusive association indicates that selective pressures have favored a unidimensional growth strategy over volumetric expansion. Additionally, the effects of immersion duration on the hatching rate and hatching time of *P. canaliculata* were investigated. A significant delay in hatching initiation was consistently observed in both the 1-day and 2-day immersion groups. Moderate reductions in hatching rates were also recorded. Immersion durations of 4–5 days were demonstrated to potentially achieve population-level control, with substantial reductions in hatching success (≥90%) and in viable offspring production documented.

Our findings also demonstrate that increasing immersion duration progressively delayed hatching and reduced hatching success. While the 1-day and 2-day immersion treatments maintained relatively high hatching rates, longer immersion periods led to delayed hatching and substantial declines in hatchability, culminating in complete hatching failure after 5 days. Therefore, prolonged immersion impairs egg viability and hatching performance.

Overall, our results indicate that water immersion for a specific duration can effectively disrupt egg development, reducing hatching success. These findings suggest that water immersion is an ecologically benign intervention for mitigating *P. canaliculata* proliferation and is likely an effective agricultural control method.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Xiaohua Bai
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Formal analysis: Jie Li,
Funding acquisition: Xiaohua Bai

Investigation: Zhiwei Tan, Leilin Yang
Methodology: Zhiwei Tan
Project administration: Xiaohua Bai
Supervision: Jie Li
Visualization: Leilin Yang
Writing–original draft: Jie Li
Writing–review & editing: Jie Li

Availability of data

Data are available from the corresponding author upon reasonable request.

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