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Behavioural Adaptations of Asian Openbills (*Anastomus oscitans*) in Preying on Invasive Apple Snails (*Pomacea* spp.)

Badrulhadza Amzah[1,2], Noorhidayah Mamat[1,*], and Rosli Ramli[1]

[1]*Institute of Biological Sciences, Faculty of Science, Universiti Malaya, Kuala Lumpur, Malaysia. *Correspondence: E-mail: nhidayahm@um.edu.my (Mamat)*
E-mail: bhadza@mardi.gov.my (Amzah); rosliramli@um.edu.my (Ramli)
[2]*Paddy and Rice Research Center, Malaysia Agricultural Research and Development Institute, Serdang, Selangor, Malaysia*

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ORCiD:
Badrulhadza Amzah: https://orcid.org/0000-0003-2902-1967
Noorhidayah Mamat: https://orcid.org/0000-0001-5353-790X
Rosli Ramli: https://orcid.org/0000-0003-0410-9604

The global proliferation of invasive freshwater mollusks poses a significant threat to agricultural productivity and ecosystem health, yet the specific behavioural adaptations that allow native predators to exploit these novel resources remain a critical research gap worldwide. In Peninsular Malaysia, the Asian Openbill (*Anastomus oscitans*), a specialist molluscivore is increasingly observed in rice fields preying on invasive apple snails (*Pomacea* spp.), which have become major pests since their introduction from South America. This study investigates the foraging behaviour and predatory efficiency of Asian Openbill across 70 locations to evaluate their potential as sustainable biological control agents and to address the lack of scientific research regarding their ecological impact in the region. Foraging activity was recorded in relation to habitat conditions, time of day, and prey type. The storks were observed primarily targeting juvenile and mature male snails while avoiding egg-bearing females, likely due to the known toxicity of their eggs. Unlike previous reports, the Openbills did not swallow small snails whole; instead, they removed the operculum and extracted the soft tissue, discarding the shells, highlighting a specialized feeding technique. Foraging intensity was highest in fields with shallow standing water, where prey accessibility was enhanced. Storks were significantly less active in dry fields, where they tended to perch or rest. Peak foraging occurred during mid-morning (0900–1000 hours) and mid-afternoon (1400–1500 hours). Shell remains were collected from a 200-meter transect in Sungai Manik, Perak, totaling 547, with a mean shell length of 31.6 mm, indicating frequent predation of medium-sized snails. In contrast, fields in Sungai Besar, Selangor recorded only seven small live snails (average 25.1 mm) and no shell remains, suggesting either low snail presence or limited predation. Sites without Openbill presence had significantly higher live snail counts (n = 88), while fields with active Openbill foraging showed fewer live snails, damaged shells, and missing operculums supporting the bird's role in reducing snail populations. These findings provide preliminary evidence that Asian Openbills exert a measurable impact on *Pomacea* density and could be integrated into rice pest management frameworks. This research demonstrates the ecological relevance of Asian Openbills in rice field ecosystems and supports their consideration as a sustainable, non-chemical alternative to conventional molluscicides. Further studies, including quantitative assessments of predation efficiency and long-term monitoring, are recommended to fully establish their utility in integrated pest management programs.

Keywords: *Anastomus oscitans*, Foraging ecology, Iinvasive species control, Molluscivore, Rice agroecosystem

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BACKGROUND

The invasion of apple snails (*Pomacea canaliculata* and *P. maculata*) has emerged as a significant ecological and agricultural challenge across Southeast Asia (Yahaya et al. 2017). Originally introduced from South America, these gastropods possess high reproductive plasticity and rapid growth rates, allowing them to establish dense populations within aquatic ecosystems (Estebenet and Martin 2002). Their biology is marked by a unique reproductive strategy in which females deposit conspicuous pink egg masses on emergent vegetation and rice stalks to avoid aquatic predation; however, these eggs are further protected by toxic perivitelline proteins that are unpalatable to most generalist predators (Giglio et al. 2016). In rice agroecosystems, their voracious herbivory on young, tender seedlings causes substantial yield losses and frequently necessitates a heavy reliance on chemical molluscicides (Yahaya et al. 2017). However, such chemical inputs have negative side effects, including water pollution, non-target mortality, and significant bioaccumulation risks in aquatic food chains. Recent studies have specifically identified the potential transfer of heavy metals, such as zinc, from contaminated mollusks to Asian Openbill hatchlings, suggesting that chemical reliance may inadvertently harm these natural predators (Tamang et al. 2025).

Given the limitations of chemical control, sustainable and eco-friendly alternatives are urgently needed. The Asian Openbill (*Anastomus oscitans*) is a promising candidate for biological control due to its specialized diet. Understanding the nutritional dynamics and feeding patterns of these storks is essential, as gastropod prey is a critical protein source for both adult maintenance and the early development of nestlings (Tamang et al. 2024). This bird, native to the Indian subcontinent and mainland Southeast Asia (Robson 2002), has evolved specialised foraging adaptations, including a unique beak morphology that allows it to efficiently extract soft tissue from hard-shelled prey (Kahl 1971). Historically, Asian Openbills preyed on native *Pila* spp. in India and Sri Lanka (Paleeri and Jayson 2018), but recent studies in Thailand have documented its successful predation on invasive *Pomacea* spp. in rice fields, highlighting its potential as a natural biological control agent (Sawangproh et al. 2012; Sawangproh 2021).

In Peninsular Malaysia, Asian Openbills were first sighted in large numbers in 2008 in Perlis (Lim et al. 2011). Previously classified as vagrants (MNS Bird Conservation Council 2010), their year-round presence, observed nesting activity (*e.g.*, in Pulau Bangau, Teluk Intan), and increased use of rice fields for foraging led to their reclassification as resident birds (MNS Bird Conservation Council 2015). This resident status has been further substantiated by recent data documenting their widespread distribution and abundance dynamics across the major rice-growing regions of Peninsular Malaysia (Amzah et al. 2025). Despite this established presence, there remains a critical need for detailed research on their specific foraging behaviors, diet, and predatory impact in the Malaysian agricultural context.

Most existing studies on Asian Openbill feeding ecology have been based in Indian wetlands and focus primarily on *Pila* spp. and other native molluscs (Datta 1992; Pramanik et al. 2009; Meganathan and Jeevanandham 2019a–d; Surya Babu and Raju Thomas 2019). These studies largely overlook agricultural settings like rice fields. In contrast, research in Thailand and recent studies in the agricultural lands of Nepal provide crucial evidence linking Asian Openbill predation to significant reductions in *Pomacea* snail abundance (Sawangproh et al. 2021; Tamang et al. 2024, 2025). These findings highlight the importance of understanding the predator-prey dynamics of Asian Openbill in human-modified landscapes, though such evidence has yet to be fully established within Malaysian rice agroecosystems. Furthermore, the predation behaviour of Asian Openbills on *Pomacea* spp. including prey selection, feeding techniques, and handling efficiency, remains under-explored. Understanding their ecological interactions with invasive snails could help evaluate their role in integrated pest management (IPM) strategies, reducing dependence on chemical molluscicides and promoting biodiversity-based solutions in rice agroecosystems.

This study aims to fill that gap by investigating the foraging and feeding behaviour of Asian Openbills in rice fields across Peninsular Malaysia. Specifically, we examine their prey selection, predation efficiency, and behavioural patterns in both wet and dry rice field conditions, and compare snail abundance between foraging and non-foraging sites.

We hypothesize that Asian Openbills can significantly reduce *Pomacea* spp. abundance through targeted and effective predation. Their presence may serve not only as a biological control mechanism but also as an ecological indicator of rice field health.

MATERIALS AND METHODS

Study area and duration

This study was conducted across 70 rice field sites distributed along the west coast of Peninsular Malaysia between September 2022 and October 2023 (Table 1). Sites were selected using stratified random sampling based on secondary data and field reports provided by the Department of Agriculture (DOA), the Department of Wildlife and National Parks (DWNP), and eBird.org. The study encompassed rice-growing regions in: Northern region: Perlis, Kedah, Seberang Perai (Penang). Central region: Perak (FELCRA Seberang Perak, Sungai Manik), Selangor (Sungai Besar). Southern region: Negeri Sembilan, Melaka, Johor (Kesang Tasek).

Table 1. Observation timeline and rice growth stages surveyed per state and seasonal cycle (September 2022 – October 2023)

State	Total Sites	Main Season (Sept '22 – Mar '23) - Growth Stages Surveyed	Off-Season (Apr '23 – Oct '23) - Growth Stages Surveyed	Asian Openbill Presence in Rice Fields
Perlis	8	PH, LP, SS	PH, LP, SS	Yes
Kedah	14	PH, LP, SS	PH, LP, SS	Yes
Penang	10	PH, LP, SS	PH, LP, SS	Yes
Perak	18	PH, LP, SS	PH, LP, SS	Yes
Selangor	11	PH, LP, SS	PH, LP, SS	Yes
Negeri Sembilan	2	SS only	SS only	No
Melaka	5	PH, LP, SS	PH, LP, SS	Yes **Roosting only
Johor	2	LP, SS	LP, SS	No
Total	70			

*PH: Post-Harvest; LP: Land Preparation; SS: Seedling Stage. **Observed not within rice fields.

Observation period and rice stage classification

Behavioural observations were carried out across 36 separate field days, between 0800 and 1800 hours, during three key rice growth phases: Post-harvest, Land preparation, and Rice seedling establishment.

Each site was visited at least once per rice season, depending on bird presence. Sites where Asian Openbills were not observed were still used for snail data comparison.

Behavioural observation protocol

A combination of scanning and focal sampling methods (Altmann 1974) was used. Birds were observed using binoculars (Bushnell Legend Ultra HD 10 × 42) and recorded with digital cameras (Nikon P950, Nikon D7200 with Sigma APO 150–500 mm telephoto lens) and smartphones (Google Pixel 3XL, 4a 5G). Sampling duration: 15 minutes per session. Replication: Minimum of 10 individual birds per site. Observer distance: From bunds or adjacent roads to avoid disturbance.

The foraging ethogram was adapted from Anam et al. (2016), with adjustments for *Pomacea* spp.

Behavioural definitions and metrics

The observed behaviour of the Asian Openbills are shown in table 2. These behavioural metrics were used to quantify foraging and feeding behaviours of the storks.

Prey items were classified into distinct developmental and sexual cohorts based on specific morphological and reproductive criteria. Juvenile snails were characterized by a shell length of less than 25 mm, while adult males were identified as sexually mature individuals with a shell length spanning 25 to 40 mm that lacked external reproductive markers (Tamburi and Martín 2008; Guo et al. 2023). Conversely, egg-bearing females were accurately distinguished by a shell length exceeding 40 mm paired with unequivocal reproductive indicators (Estebenet and Martín 2002), specifically the presence of conspicuous pinkish egg masses attached directly to the shell surface, or a significantly distended, dark-colored fleshy foot area near the operculum, which is a diagnostic trait characteristic of gravid individuals within *Pomacea* spp.

Table 2. Operational definitions of behavioural metrics used to quantify foraging and feeding behaviour of Asian Openbills (*Anastomus oscitans*) in rice fields of Peninsular Malaysia

Behavioural Metric	Definition
Probe Rate	Number of beak insertions per minute during active foraging
Prey Success	Total number of prey captured per unit of foraging time
Prey Capture Rate	Number of successful captures per minute per individual
Prey Handling	Observed strategies (*e.g.*, operculum removal, shell discarding)
Feeding Selectivity	Preference based on prey type (juvenile, adult male, egg-bearing female)

Snail surveys

Snail surveys were conducted at selected sites in Perak (Sungai Manik), Selangor (Sungai Besar), Kedah (Kuala Muda), and Johor (Kesang Tasek).

At each site: A 200-meter transect was walked. All live, dead, and empty shells were recorded. Shell length was measured using digital calipers to the nearest 0.1 mm. Field signs such as damaged shells, missing operculums, and evidence of predation were noted.

Comparative surveys were made between fields with and without Openbill presence to assess the effect of predation.

Data analysis

Data were analyzed using both descriptive and quantitative inferential statistics to evaluate the behavioural and ecological impact of Asian Openbills. To determine the influence of field conditions on predatory activity, a Chi-square test of independence was employed to compare foraging frequency between inundated and dry rice plots. The selectivity of prey sex and size classes was assessed using a Chi-square Goodness-of-Fit test, comparing observed predation frequencies against expected null distributions derived from local baseline field availability. Spatial differences in live snail abundance and density between foraging and non-foraging sites were evaluated descriptively and interpreted with caution due to sample size constraints.

Variations in mean snail shell lengths between consumed prey remains and live field populations within the same site were evaluated using an independent samples t-test. All inferential statistical analyses were conducted with a significance threshold of $p < 0.05$. Additionally, high-resolution photographs and digital video records were utilized to qualitatively describe and illustrate specialized foraging techniques, prey handling cycles, and site-specific feeding behaviours.

RESULTS

Foraging strategy and grouping behavior

Asian Openbills exhibited flexible foraging strategies, ranging from solitary individuals to large flocks exceeding several hundred birds (Fig. 1a–b). This flexibility allows them to adjust their foraging behaviour in response to a range of social and environmental conditions. Foraging group sizes varied depending on rice growth stages, habitat conditions, and prey availability.

Flock foraging was commonly observed in areas with high prey availability and standing water. In Kampung Gajah, Perak, the percentage of active foraging varied with water levels and rice stage (Table 3).

Temporal feeding patterns

Feeding peaked during early morning (0900–1000 hours) and afternoon (1400–1500 hours). In this study, Asian Openbill were observed foraging throughout the land preparation period (from the initial tillage stages until before flooding) and across all growth stages, particularly during seedling establishment and active tillering, as well as post-harvest. (Fig. 1c–g).

Fig. 1. (a) An individual of Asian Openbill searching for preys in Bukit Meriam, Kota Kuala Muda, Kedah on 12 January 2023; (b) A flock of Asian Openbill foraging was observed at Sungai Besar, Selangor on 4 October 2023; (c) An Asian Openbill forages during rice land preparation stages (dry tillage); (d) An Asian Openbill forages during rice land preparation stages (wet tillage); (e) The foraging activities of the Asian Openbill during seedling stage; (f) The foraging activities of the Asian Openbill during active tillering stage; (g) An Asian Openbill was observed catching an apple snail after rice harvesting stage.

Table 3. Percentage of individual Asian Openbill actively foraging at different times and rice stages (Kampung Gajah, Perak)

Date	Time of observation	Location (Observation Point)	Rice stage	% of foraging individual Asian Openbill
5/9/ 2022	10.30 am	Block 6 FELCRA Seberang Perak (Location 1)	After harvest (dry field)[a]	(14/74) x 100 = 18.9%
5/9/ 2022	2.00 pm[b]	Block B Ulu Dedap (Location 2)	Land preparation (after 2nd tillage, standing water)	(265/442) X 100 = 59.9%
13/9/ 2022	10.30 am	Block 6 FELCRA Seberang Perak (Location 1)	Land preparation (Dry tillage)	(7/7) x 100 = 100%[c]
13/9/ 2022	10.00 am[b]	Block B Ulu Dedap (Location 3)	Land preparation (after 2nd tillage, no standing water)	(27/52) X 100 = 51.9%
13/9/ 2022	12.00 pm	Block D Ulu Dedap (Location 4)	Land preparation (after 2nd tillage, standing water)	(33/33) X 100 = 100%c
22/9/ 2022	11.30 am[b]	Block D Ulu Dedap (Location 5)	Land preparation (after 2nd tillage, standing water)	(75/172) X 100 = 43.6%
23/9/ 2022	9.30 am	Block 6 FELCRA Seberang Perak (Location 6)	Land preparation (after 2nd tillage, no standing water)[a]	(20/74) X 100 = 27%
15/10/2022	2.00 pm[b]	Block D Ulu Dedap (Location 5)	Rice seedling (two weeks after seeding)[d]	(17/27) x 100 = 62.9%
29/10/2022	9.30 am[b]	Block 6 FELCRA Seberang Perak (Location 6)	Rice seedling (two week after seeding)[d]	(61/92) X 100 = 66.3%
29/10/2022	12.00 pm[b]	Block D Ulu Dedap (Location 5)	Rice seedling (one month aft er seeding)[d]	(16/64) x 100 = 25%

[a]Influenced by field conditions, [b]Influenced by time of the day, [c]Influenced by flock size, [d]Influenced by food source.

Influence of field conditions

Asian Openbills displayed higher foraging activity and prey capture success in flooded rice fields than in dry fields (Table 4). Statistical analysis confirms that the storks showed a significant preference for foraging in fields with standing water compared to dry plots ($\chi^2 = 48.74$, $d.f. = 1$, $p < 0.001$; Table S1). Foraging activity was more than twice as likely to occur in inundated plots (mean = 55.1%) than in dry fields (mean = 22.9%), suggesting that microhabitat hydrology is a primary driver of predatory efficiency. In waterlogged plots, probing rates doubled (31.8/min) compared to dry areas (16.2/min), and snail capture rates also increased (2.6 vs. 1/min) (Table S2), indicating that moist environments facilitate snail detection and capture.

Table 4. Percentage of foraging individuals in rice fields with and without standing water across five sampling locations

Date	Location point	Rice field condition	% of individual birds showing foraging activities
5/9/ 2022	Block 6 FELCRA Seberang Perak (1st location)	No standing water	18.9% (14/74)
5/9/ 2022	Block B Ulu Dedap (1st location)	Standing water	59.9% (265/442)
13/9/ 2022	Block B Ulu Dedap (2nd location)	Standing water	51.9% (27/52)
22/9/ 2022	Block D Ulu Dedap	Standing water	43.6% (75/172)
23/9/ 2022	Block 6 FELCRA Seberang Perak (2nd location)	No standing water	27% (20/74)

Prey handling and consumption techniques

Observations revealed that Asian Openbills did not swallow small apple snails whole as previously reported (Kahl 1971), but instead removed the operculum and extracted the soft body (Fig. 2a–f). Feeding duration was brief, with each capture-to-consumption cycle lasting less than 5 seconds (n = 10). Larger snails were often processed on rice bunds, where the birds used stable ground to extract soft tissues. However, in Pinang Tunggal, Kepala Batas, we managed to observe an Asian Openbill discarding a large apple snail in a water canal without carrying it out to dry ground (Fig. 2g–h).

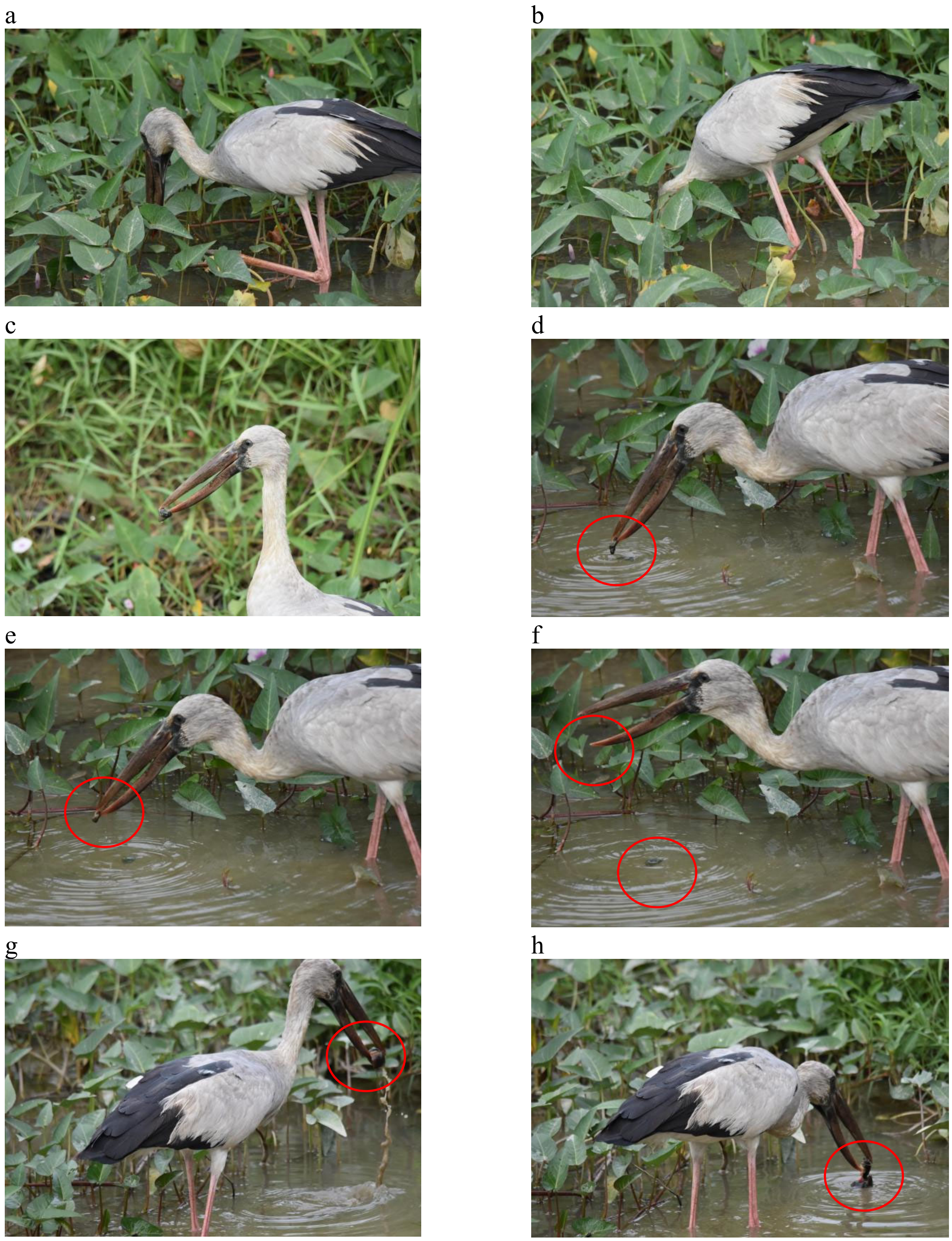

Fig. 2. Prey searching and consumption process of smaller apple snail by an Asian Openbill: (a) Wading in the shallow water, probing slowly with its slightly open beak; (b) Probing intensity increased when the beak detected the presence of prey utilising the tactile sense, beak was inserted 2/3 of its length into the water; (c) The captured prey was picked up using the tip of its beak; (d) Mud cleaning for the snail shell. The soft body of the snail was separated from the operculum and shell using both the upper and lower beaks, shaking repeatedly at fast rate; (e) The soft snail body was successfully extracted from its shell; (f) The stork raised its head, opened its beak, and swallowed the snail's body. The empty snail shell had been dropped in the water. No crushing of shell observed; Prey searching and consumption process of larger apple snail: (g & h) An Asian Openbill was observed processing its captured larger prey *in situ*.

Prey selection and avoidance of egg-bearing females

Asian Openbills selectively consumed juvenile and mature male snails while avoiding larger, egg-bearing females. A Chi-square Goodness-of-Fit test on representative shell remains (n = 11) collected at Sungai Manik was conducted using empirical ratio of juvenile/male to female snails observed in the local field population (60% targeted : 40% avoided baseline ratio) as the expected null distribution. The storks demonstrated a non-random preference for targeted size classes over large females relative to their field availability ($\chi^2 = 4.38$, *d.f.* = 1, $p = 0.0364$; Table S3). This avoidance matches the known toxicity profiles of mature *Pomacea* egg masses. Visual field evidence, including discarded damaged shells and intact operculums found alongside missing soft tissue, further supports this specialized prey handling strategy (Fig. 3a–b).

Shell deposition patterns

Comparison of snail shell sizes revealed a geographic variance between the empty shell remains recorded at Sungai Manik and the live individuals collected at Sungai Besar (Fig. 3c). A 200-meter transect in Sungai Manik yielded empty shell remains with a mean length of 31.6 ± 6.64 mm (n = 11 representative samples). In contrast, fields in Sungai Besar yielded only seven small live snails with a mean length of 25.1 ± 6.04 mm (n = 7), with no empty shell remains found at the site. An independent samples t-test confirmed that the mean sizes differed significantly between these two sampled locations ($t = 2.09$, *d.f.* = 16, $p < 0.05$; Table S4). These variations indicate a landscape-level difference in observed snail sizes across regions, which may reflect unequal localized foraging pressures or differing baseline snail population age structures between the two farming zones.

a b c

Fig. 3. (a) The missing operculum and damaged shells with small holes caused by stork's beak; (b) The dead female snails found on rice bund with egg clusters; (c) Large empty shells were discarded on the rice bund, indicating that Asian Openbill consumed the large snails on the bund.

Shell suppression and population impact

Observational counts between active foraging landscapes and non-foraging control zones showed a localized variance in raw snail abundance. Live snail counts recorded during baseline surveys were lower at the active foraging site (Sungai Besar, n = 7) than at the reference site where storks were absent (Kesang Tasek, n = 88). Qualitative visual monitoring at additional foraging areas in Kodiang and Pendang revealed frequent occurrences of characteristic predatory field signs, including freshly damaged shells and missing operculums, which were absent in control plots. These descriptive trends point to a potential link between sustained stork presence and depressed pest numbers, though multi-season replicate sampling across wider geographic blocks remains necessary to verify broad ecological suppression.

Resting, roosting, and soaring behavior

When not feeding, birds rested on bunds and tree canopies, often using the same trees for nocturnal roosting. In Perak, flocks were seen returning to Pulau Bangau for roosting. Midday soaring (Fig. 4) may serve thermoregulatory or scouting functions, a behavior also noted in similar stork species.

Fig. 4. Soaring usually occurred at midday. Later, the Asian Openbills either changing their feeding ground or landing at the same spot again.

DISCUSSION

This study highlights the ecological importance of the Asian Openbill in rice agroecosystems of Peninsular Malaysia, particularly its role as a natural predator of the invasive apple snail. Field observations demonstrated that the stork adapts its foraging strategy according to habitat conditions, ranging from solitary foraging to large flock behaviour. This flexibility suggests that the species optimizes feeding efficiency based on prey availability and social facilitation, a pattern consistent with observations of the species in varied ecological contexts in Thailand and India. (Ishtiaq et al. 2010; Sawangproh 2021). The preference for flooded rice fields further reinforces the importance of microhabitat hydrology in supporting efficient foraging by wading birds, as inundated fields enhance prey visibility and mobility, facilitating higher probe and capture rates.

Temporal feeding activity was concentrated during early morning and late afternoon, aligning with periods of cooler temperatures and potentially increased snail activity near the water surface. Although snail behaviour was not directly monitored, the synchronicity between peak Asian Openbill foraging and the known periods of high snail surface activity suggests an adaptive predator response (Kahl 1971; Sawangproh et al. 2012). This temporal alignment likely optimizes foraging efficiency by maximizing energy intake while reducing search and handling time. The observation of storks foraging across all rice growth stages and post-harvest periods aligns with earlier findings regarding the species' use of wetland and agricultural mosaics. Similar diurnal feeding patterns have been observed in other malacophagous species, such as the Snail Kite (*Rostrhamus sociabilis*) and the Limpkin (*Aramus guarauna*), reflecting evolved strategies to exploit temporally predictable prey movements (Sawangproh et al. 2012; Giglio et al. 2016).

The feeding mechanics of the Asian Openbill observed in this study differed from previously documented accounts. Contrary to earlier descriptions that the bird swallows small snails whole (Kahl 1971), our field observations reveal that the stork employs a specialized handling technique. The operculum is first removed before the soft tissue is extracted and consumed, while the shell is discarded. This strategy appears to be consistent across snail size classes and may reflect anatomical adaptations of the Openbill's beak morphology. Prey selection was also non-random; birds showed a tendency to avoid egg-bearing females. This selective foraging is likely due to the known toxicity of perivitelline fluid (PcPV2, PcOvo) in Pomacea egg masses, which are unpalatable or harmful to predators. This behaviour is consistent with observations of adaptive prey discrimination in other regions (Giglio et al. 2016). The selective foraging behaviour suggests not only a degree of prey discrimination but also a potentially learned or innate avoidance of toxic prey.

In this study, Asian Openbills exhibited spatial flexibility in prey handling by selecting specific microhabitats based on snail size and processing requirements. Larger apple snails were often transported from wet paddies to dry bunds or raised ground, where stable surfaces allowed better leverage for operculum removal and tissue extraction. This behaviour was especially evident at sites like Sungai Manik, Perak, where a high number of large empty shells were found on bunds.

This supports similar findings by Sawangproh (2021), who noted that Openbills use the physical surroundings to aid in feeding efficiency. Conversely, medium and small-sized snails were typically handled in situ within shallow water plots, requiring less manipulation and no need for relocation. Observations at Kepala Batas, Seberang Perai, also showed that large snails were occasionally processed in water, suggesting that the storks' adaptability may extend to handling strategy as well. The presence of smaller discarded shells underwater, often undetected during standard shell counts, further highlights the species' nuanced feeding ecology. These patterns of microhabitat selection and prey-specific handling underscore the Openbill's behavioural plasticity, optimizing foraging efficiency through site-specific strategies that minimize energy expenditure and maximize success. Such flexibility reinforces the bird's potential as an effective and sustainable biocontrol agent in rice field ecosystems.

The evidence of predation on apple snails was further supported by the high abundance of empty shells and damaged operculums at active foraging sites compared to control plots without stork presence. Shell length analysis indicated prey size selectivity, with a preference for juvenile and male snails, aligning with the physical handling limitations of the bird's mandibles. Sites like Sungai Manik showed significantly higher shell deposition (547 shells in a 200-meter transect) compared to sites like Sungai Besar, which yielded only a few small-sized snails and no shells. In areas without Openbill activity, such as Kesang Tasek in Johor, live snail populations were markedly higher. These spatial differences suggest a localized impact of Openbill predation, with implications for the natural regulation of pest populations.

Behavioural observations also recorded the storks resting and roosting on field bunds and nearby trees during non-feeding periods. In particular, the repeated use of Pulau Bangau as a roosting site supports its significance as a central node in the birds' daily foraging cycle. Such spatial structuring, with foraging dispersed across multiple fields and roosting centralized in one secure location, reflects patterns common in colonial wading birds and emphasizes the need to conserve both feeding and roosting habitats (Kumar and Kanaujia 2016; Mohapatra et al. 2019).

The findings of this study provide robust field-based evidence that Asian Openbills can exert measurable predation pressure on apple snail populations in rice fields. While not a substitute for all pest control methods, their contribution can complement integrated pest management strategies, particularly in reducing reliance on molluscicides that may harm non-target organisms and degrade aquatic ecosystems (Yahaya et al. 2017). Promoting environmentally friendly farming practices that accommodate stork foraging, such as maintaining flooded fields during early crop stages, preserving roosting habitats, and minimizing disturbance can help align conservation goals with agricultural productivity.

Nevertheless, this study has limitations. Prey availability was inferred indirectly through shell counts and live snail surveys rather than controlled snail density measurements. Furthermore, true within-site size-selective predation preference could not be definitively isolated, as shell size data were structurally uncoupled across locations, consisting exclusively of empty prey remains in Sungai Manik and live individuals in Sungai Besar. Future ecological tracking must prioritize measuring co-occurring live populations and discarded shell remains within identical plots to statistically confirm active size selection by the birds. The contribution of other potential snail predators, including rats, fire ants, and other birds, was not isolated and should be investigated in future studies. Moreover, prey handling and success were documented descriptively; future efforts should incorporate quantitative ethogram analysis and motion-triggered video surveillance to strengthen behavioural metrics.

CONCLUSIONS

Asian Openbills (*Anastomus oscitans*) demonstrate strong potential as natural biological control agents against invasive apple snails (*Pomacea* spp.) in Malaysian rice agroecosystems. This study provides clear field-based evidence of their adaptive foraging behaviour, prey selectivity, and ability to reduce snail populations in areas where they are active. By targeting juvenile and adult snails while avoiding toxic egg-bearing females, Openbills present an ecologically efficient and species-specific form of pest control.

The findings underscore the relevance of integrating Asian Openbills into sustainable rice field management strategies, particularly in regions where chemical molluscicides are overused. Their presence not only supports natural pest regulation but also contributes to the ecological resilience of rice landscapes and biodiversity conservation.

To maximize the benefits of this native predator, future efforts should focus on enhancing suitable foraging and nesting habitats, minimizing disturbances during critical feeding periods, and promoting coexistence with farming communities through education and policy support. Long-term ecological monitoring is also essential to assess population dynamics, foraging impact, and to ensure the sustained role of Asian Openbills in controlling apple snail infestations.

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Competing interests: The authors declare that there are no conflicts of interest associated with this research.

Availability of data and materials: The data supporting the findings of this study are available within the article and its supplementary materials. The full spreadsheet containing our raw transect snail counts, bird count tallies, and snail measurement metrics also has been securely uploaded to FigShare (10.6084/m9.figshare.32751813)

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Ethics approval consent to participate: Not applicable.

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Supplementary materials

Table S1. Chi-square test of independence for foraging activity in relation to field water conditions. (download)

Table S2. Probing and capture rate in fields with and without standing water. (download)

Table S3. Chi-square Goodness-of-Fit test for prey sex and type selection at Sungai Manik based on the local field population baseline ratio (60% targeted : 40% avoided). (download)

Table S4. Independent Samples t-test for snail shell length between Sungai Manik and Sungai Besar. (download)